PL-TR--94-1131

PL-TR--
94-1131

ZENITH STAR SUPPORT EXPERIMENT DESIGN

Dr. J. William Dettmer

Lockheed Missiles & Space Company, Inc.
6400 Uptown Blvd NE, Suite 300 West
Albuquerque, NM 87110

May 1995

Final Report

PHILLIPS LABORATORY
Space and Missiles Technology Directorate
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

PL-TR--94-1131

This final report was prepared by the Lockheed Missiles & Space Company, Albuquerque, New Mexico under Contract F29601-89-C-0015, Job Order 13050405 with Phillips Laboratory, Kirtland AFB, New Mexico. The Laboratory Project Officer-in-Charge was Ronald R. Ninneman (VTSS).

This report has been reviewed and is approved for publication.

RONALD R. NINNEMAN
Project Officer

FOR THE COMMANDER

L. KEVIN SLIMAK, GM-15
Chief, Structures and Controls Division

HENRY L. PUGH, JR., Col, USAF
Director of Space and Missiles Technology

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1995	Final Jul - Nov 90

4. TITLE AND SUBTITLE
ZENITH STAR SUPPORT EXPERIMENT DESIGN

5. FUNDING NUMBERS
C: F29601-89-C-0015
PE: 63221C
PR: 1305
TA: 04
WU: 05

6. AUTHOR(S)
Dr. J. William Dettmer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lockheed Missiles & Space Company, Inc.
6400 Uptown Blvd NE, Suite 300 West
Albuquerque, NM 87110

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Phillips Laboratory
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
PL-TR--94-1131

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Experiments are proposed that can be performed on the SPICE structure in support of the Zenith Star Experiments. The fourteen experimental proposals fall into four categories: isolation of a space beam expander from on-board disturbances, evaluation of pointing and tracking systems, uses of advanced materials and passive damping, and characterization of disturbances. At least four experiments are proposed in each category. Those rated most valuable by Zenith Star personnel include: advanced composite materials studies, admittance modeling of a passive structure, and further research into the capabilities of the Space Active Vibration Isolation System (SAVI).

14. SUBJECT TERMS
Control system design, Digital control, Kalman filters, Multivariable control system, Active isolation, Vibration control, Space-based laser

15. NUMBER OF PAGES
126

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

CONTENTS

CONTENTS (CONCLUDED)

FIGURES

FIGURES (CONCLUDED)

TABLES

1.0 INTRODUCTION

1.1 Subtask Goals and Methodology

This document is the final report of the Zenith Star Support Experiment Design Subtask of the Space Integrated Controls Experiment (SPICE) Program. The goal of the Subtask was to produce conceptual designs of experiments to be performed on the SPICE apparatus in support of the Zenith Star Experiments: the Zenith Star Flight Experiment, the Alpha/LAMP Integration (ALI) Experiment, and the Complementary Space Experiment (CSE).

The Statement of Work required that experiments be proposed in the following four areas:

1- Isolation between a high energy laser device and a beam expander

2- Evaluation of proposed Zenith Star pointing and tracking control systems

3- Use of advanced materials and passive damping in a high energy laser system

4- Characterization of vibrational disturbances, especially those due to coolant flow in a cooled secondary mirror

The study team consisted of personnel from the SPICE contractor (Lockheed) and two of the SPICE subcontractors (Honeywell and CSA Engineering) with Lockheed Zenith Star Program personnel serving as consultants. Experiment concepts were proposed and discussed by study team members and Zenith Star personnel in a three-day integration meeting. Each proposed experiment that was found to be viable and applicable to Zenith Star needs was then assigned to an appropriate member of the study team for development of the concept and for estimation of experiment cost and schedule.

1.2 Results of the Subtask

The subtask produced 14 experiment conceptual designs, with at least three in each of the four required areas. These are briefly discussed here; more detail is provided in the main body of the report.

1.2.1 Isolation Experiments

1- <u>Passive isolation of a space-based laser component</u>: The effectiveness of specific techniques for isolating, e.g., a beam transfer assembly from a spacecraft would be quantified.

2- <u>Isolation of a beam expander</u>: Techniques less extensive than the Space Active Vibration Isolation (SAVI) system that has already been chosen for the Flight Experiment might be required in a

smaller space experiment such as CSE . The effectiveness of candidate isolation methods would be quantitatively compared.

3- Further SAVI research: This would involve further investigation and upgrading of the active isolation method that has already been designated as required for the Zenith Star Flight Experiment.

1.2.2 Pointing and Tracking Control Experiments

1- Active control of primary mirror segments: The current Zenith Star Flight Experiment design specifies that the Large Advanced Mirror Program (LAMP) mirror segment actuators be used only in alignment to attain correct mirror shape. In this proposed experiment, the improvement in line of sight maintenance and beam quality to be had from active control of primary mirror segments would be investigated.

2- ALI primary mirror - secondary mirror alignment system investigation: The ALI design includes a low bandwidth primary mirror-secondary mirror alignment system for compensating for low frequency disturbances such as thermal drift. It is proposed to test the effectiveness of this alignment system by simulating it on the SPICE apparatus.

3- High performance slewing of a Zenith Star beam expander surrogate: The Zenith Star Flight Experiment has retargeting demonstration goals that require rapid slewing of the beam director. This experiment would investigate methods for achieving rapid slewing without degrading line of sight and wavefront quality.

4- Separate aperture tracker effects: The Zenith Star Flight Experiment will have a separate aperture tracker that must be boresighted with the beam director. In this experiment both the boresighting scheme and the effects of the tracker mass would be investigated.

5- Use of smart struts in a Zenith Star beam expander surrogate: ALI or the Zenith Star Flight Experiment will require damping of the vibrational disturbances in the beam expander. In this experiment, the utility of smart struts, i.e. struts with internal active control, as metering structure legs would be evaluated on the SPICE apparatus.

1.2.3 Advanced Materials and Passive Damping Experiments

1- Advanced composite materials experiment: Performance improvement from the use of the very stiff composite materials as legs on the quadrapod metering structure of the Zenith Star Flight Experiment or ALI would be evaluated by using struts made of such materials as tripod legs on the SPICE apparatus metering structure. The prime advanced material candidates for this experiment appear to be Graphic/Magnesium and Graphic/Aluminum.

2- Passive damping of tripod (or quadrapod) modes of a beam expander: This effort would be an analytical extension to the Zenith Star quadrapods of the experimental results on viscoelastic damping of low order modes of the SPICE tripod. The tripod damping experiments are planned as part of another SPICE Subtask.

3- Passive damping of modes of a segmented mirror: The effect on beam quality and line of sight maintenance of the use of viscoelastic damping on the attachments of the primary mirror segments to the main structure would be investigated in this experiment.

1.2.4 Disturbance Characterization Experiments

1- Mirror coolant flow disturbance characterization by admittance modeling on a passive structure: Parametric evaluation of this disturbance for the ALI and Zenith Star Flight Experiment secondary mirrors can be done accurately by the combination of experiment and theory known as admittance modeling. In this experiment, the admittance modeling method would be verified on the SPICE apparatus and then extended to the Zenith Star structures using their finite element models.

2- Mirror coolant flow disturbance characterization by admittance modeling on an active structure: The Zenith Star Flight Experiment beam expander is not now envisioned to be actively controlled. As active structural control methods become better understood through such programs as SPICE, it may become desirable to use them on the Zenith Star Flight Experiment or other space-based directed energy systems. This experiment would extend the previous one to the significantly more complex environment of an actively controlled structure.

3- Computational Fluid Dynamics Model to Predict Coolant Flow Disturbances: The optimum solution to the problem of characterization of coolant flow disturbances would be to have a purely computational tool that performed the characterization accurately. Such tools appear to be emerging but they are not yet ready to challenge the semiempirical method of admittance modeling. This effort would investigate the state of the art of the use of computational fluid dynamical computer codes for coolant flow disturbance characterization.

1.3 Evaluation of Proposed Experiments

At the conclusion of the Subtask technical effort, the Assistant Program Manager/Technical evaluated the experiment conceptual designs for their value to the Zenith Star Program as it is currently structured. His evaluation is provided in Section 6.

2.0 THE SPACE INTEGRATED CONTROLS EXPERIMENT (SPICE)

2.1 Purposes/Goals of SPICE

SPICE is an applied research program to investigate and demonstrate in an integrated large-scale experiment :

- Isolation of structures from disturbance sources
- Active control of structural vibration
- Passive damping of structural vibration
- Use of advanced materials in structures
- Use of adaptive optics for rejection of the effects of disturbances

The integration of technologies developed on other programs as well as development of additional hardware required for that integration and of appropriate computer models are within its scope. It serves, therefore, as an important demonstrator and model in support of current and future programs such as:

- Zenith Star
- Space Based Laser Concept Formulation & Technology Development Program
- Ground Based Laser Concept Formulation & Technology Development Program
- Neutral Particle Beam

When completed, the SPICE apparatus will be the most versatile test bed in existence for directed energy systems.

2.2 Brief Description of SPICE Apparatus

Space-based directed energy weapons will require isolation of the beam expander from the vibrational disturbances that are generated by the source of the directed energy. The Space Active Vibration Isolation (SAVI) system, already identified as the technology of choice for that isolation, is a major portion of the SPICE structure shown in Figure 2.2.1. Figure 2.2.2 shows a cartoon of the SPICE structure that is useful in identifying its various components. A brief discussion of the apparatus is presented here as an adjunct to the proposed experiments of Section 5. Referring to Figure 2.2.2, three pairs of shakers input vibrational disturbance to the system through the aft-body simulator mass immediately above them. Immediately above the aft-body simulator are two layers of actuators, with each containing three pairs of elements. The lower one, labelled 'linear', has a stroke of ±12.7 cm and is effective in isolating the foreword body from low frequency disturbances. The other layer is magnetic, has gap motion of ±2.5 mm and is effective in high-frequency isolation. Immediately above the truss is the seven segment primary mirror simulator which is designed to behave mechanically similarly to the Large Advanced Mirror Program (LAMP) mirror which is the Zenith Star primary mirror. The secondary mirror simulator is supported by a

tripod. The weight of the structure is supported by a gravity offload system that connects the ceiling of the room with the center segment of the primary mirror surrogate which in turn is rigidly fastened to the truss beneath it. Key features of the apparatus are:

- The SAVI system is integrated with a beam expander simulator
- The beam expander is large enough to provide good traceability to a directed energy weapon
  - Primary mirror simulator has seven segments, with overall diameter ≈ 5.6 m
  - Primary to secondary distance ≈ 6.6 m
- Two-axis slewing of ±2° is available via the SAVI actuators

It is important to note that the existence of an optical scoring system (OSS) is assumed in some of the proposed experiments described in later sections of this report. Its purpose is to provide observations of line of sight jitter and low order wavefront distortion due to rigid body displacements and rotations of the simulators of the secondary mirror and primary mirror segments. This is accomplished using readings of six two-axis tilt sensors, six two-axis gap sensors, and six three-axis gap sensors. The gap sensors measure relative displacements of adjacent segment of the primary mirror surrogate. The tilt sensors measure tilt with respect to the center segment of the primary via laser beams reflected back to the center petal from small reflectors on each of the other six segments. Probe beams are also used in measuring the displacement and orientation of the secondary with respect to the center primary segment. Figure 2.2.2 shows the OSS probe beams and optical sensor heads. Design of the OSS has, at this writing, reached the Critical Design Review stage. Further discussion of the OSS may be found in Reference 1.

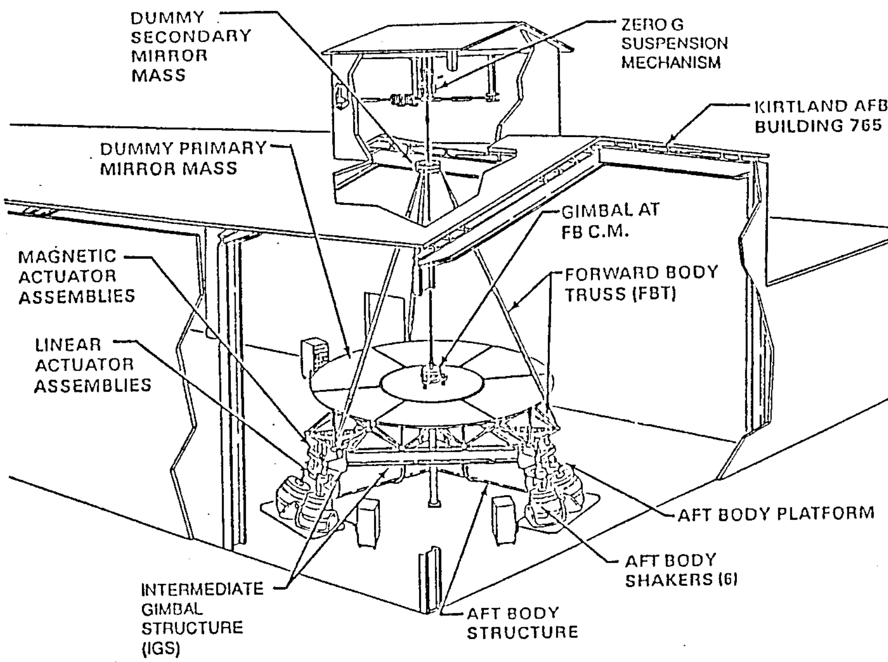


Figure 2.2.1 The SPICE apparatus.

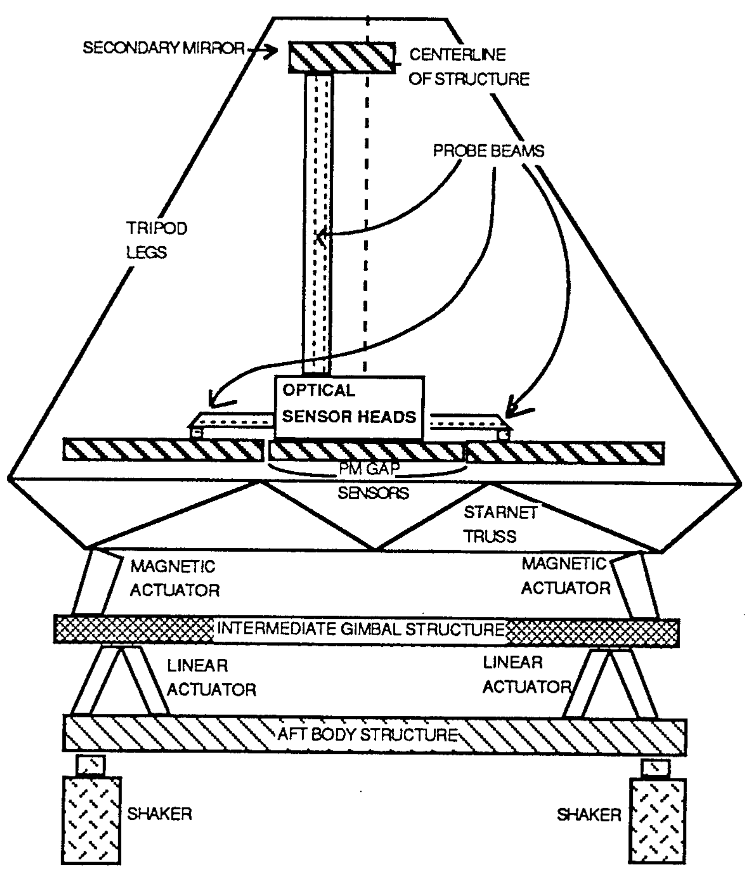


Figure 2.2.2 Schematic of SPICE apparatus with the Optical Scoring System.

3.0 THE ZENITH STAR EXPERIMENTS

The Zenith Star experiments are a set of three experiments designed to demonstrate technology for a future SBL system:

- The Zenith Star flight experiment
- The ALI experiment
- The CSE

It is the objective of this subtask to support the Zenith Star experiments, which are briefly described here.

3.1 Zenith Star Flight Experiment

The objectives of the Zenith Star flight experiment are to provide demonstrations and evaluations of an integrated high power laser system in space and to provide data in many of the areas that are required for an informed decision on a near term space-based laser system. Separately launched targets will be engaged for demonstrations of fluence, pointing, tracking, etc. in the 60 - 300 km range. Figure 3.1.1 depicts the Zenith Star space vehicle, with the two portions that would be launched separately shown before docking. The objectives of this ambitious program, as determined by the Zenith Star Scientific Advisory Board,are listed in Tables 3.1.1 and 3.1.2 in order of priority within each technology area and overall priority.

Some of the details of the Zenith Star flight experiment are presented here to provide comparisons with the SPICE apparatus. Figure 3.1.2 depicts the Zenith Star beam expander. The primary mirror of the Zenith Star is the seven-segment LAMP mirror which has a diameter of 4.0 m and an f-number of 1.25. One of the segments is in the shadow of the Alpha laser feedback and is replaced by the capture and track subsystem. The Zenith Star secondary mirror is provided with coolant flow through the legs of the quadrapod support structure. There is no active structural control of the foreword body; passive isolation and damping techniques are employed.

A series of five experiments, three high power and two low power, are planned to meet the Zenith Star goals listed in the first two tables.

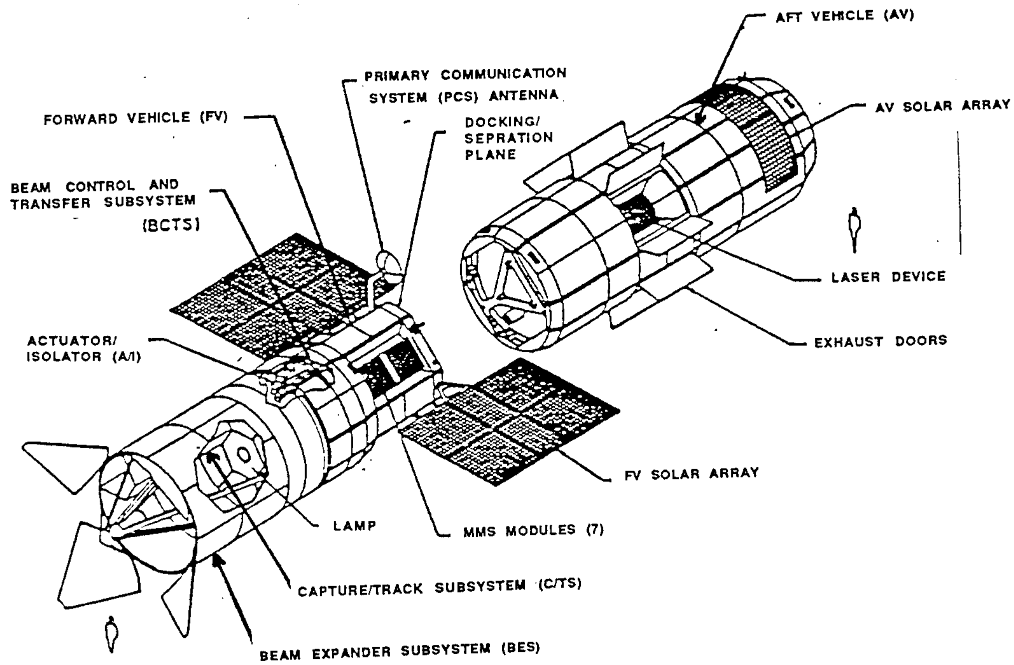


Figure 3.1.1. The Zenith Star Space Vehicles

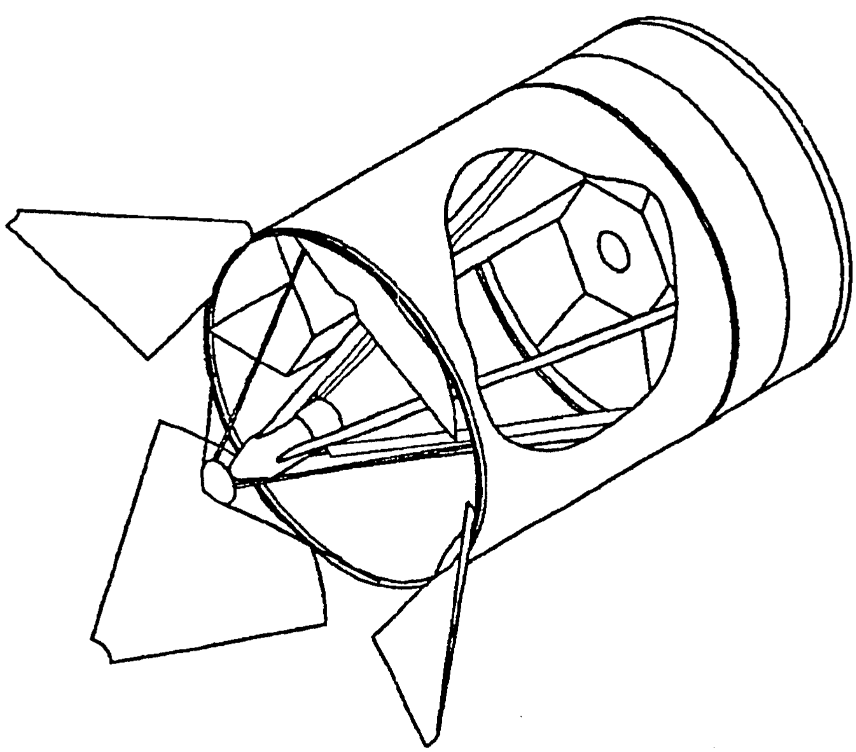


Figure 3.1.2. The Zenith Star Beam Expander.

	1 PRIMARY	2 MIDCOURSE	3 PRECISION TRACKING	4 AGILE PLATFORM	5 DATA	6 OTHER
1	Solid Booster	Light Decoy	Track at High Power	Multi-Target Low-Power Retargeting Performance Demo	Signatures Boost, PBV, Decoys (Active and Passive)	Surveillance Demo
2	Liquid Booster	Impulse Discrimination	Hardbody Handover	System Characterization	Observables at Low Power	Scoring SDIO Experiments
3	Beam Characterization	Passive Discrimination	Active Track Demonstration	Coordinated Motion-Integrated Beam Steering	Induced Backgrounds	Space Operations
4	Validate Performance	Active Discrimination	Passive Track Demonstration	Integrated High-Power Rapid Retargeting	Natural Backgrounds	Uplink/Downlink Experiment
5	Self Defense	Thermal Tag	Multi-Target Track	Integrated Timeline Experiment	Bistatic Data	Laser Communications
6	Effectiveness in Atmosphere		Track Various Targets	Active Structure Control	Plume Interaction	Bifocal Relay
7			Countermeasures			Astronomy
8			Retarget Impact on Image and Track			
9			Compare Aperture Size Performance and Boresight			

Table 3.1.1. Zenith Star Flight Experiment Objectives.

FIRST PRIORITY "MUST ACCOMPLISH"	SECOND PRIORITY "HIGH PAYOFF"	THIRD PRIORITY "AS AVAILABLE
1.1 Solid Booster	3.5 Multi-Target Track	6.2 Scoring SDI Experiments
1.2 Liquid Booster	2.3 Passive Discrimination	6.3 Space Operations
2.1 Light Decoy	2.4 Active Discrimination	1.6 Effectiveness in Atmosphere
2.2 Impulse Discrimination	4.2 System Characterization	6.4 Uplink/Downlink Experiment
3.1 Track at High Power	2.5 Thermal Tag	5.6 Plume Interaction
1.3 Beam Characterization	4.3 Coordinated Motion-Integrated Beam Steering	6.5 Laser Communications
4.1 Multi-Target Low-Power Retargeting Performance Demo	5.2 Observables at Low Power	6.6 Bifocal Relay
3.2 Hardbody Handover	1.5 Self Defense	6.7 Astronomy
1.4 Validate Performance	6.1 Surveillance Demo	
3.3 Active Track Demonstration	4.4 Integrated High-Power Rapid Retargeting	
3.4 Passive Track Demonstration	3.6 Track Various Targets	
5.1 Signatures Boost, Post Boost Vehicle, Decoys (Active and Passive)	3.7 Countermeasures	
	4.5 Integrated Time line Experiment	
	5.3 Induced Backgrounds	
	3.8 Retarget Impact on Image and Track	
	5.4 Natural Backgrounds	
	3.9 Compare Aperture Size Performance and Boresight	
	4.6 Active Structure Control	
	5.5 Bistatic Data	

Table 3.1.2. Zenith Star Flight Experiment Objective Priorities.

3.2 Alpha/LAMP Integration Experiment

Zenith Star Program constraints have led to a concentration of current efforts on ALI, which is a risk reduction ground test of some key Zenith Star technologies. The objective is to use existing ground facilities to the greatest possible extent in devising a system in which the Alpha hydrogen fluoride high energy laser (HEL) and the LAMP mirror are integrated into a single system. The Alpha laser beam will be relayed to a beam expander that has the LAMP mirror as its primary. The HEL and the beam expander will be on separate optical benches. The goals of ALI are listed in Table 3.2.1. The combining of the LAMP mirror and the Alpha laser into a single system will provide a large data base concerning the actual engineering problems associated with HEL systems. SPICE and ALI can function as partners in risk reduction for Zenith Star. The former will deal with the problems of running a large noisy powerful laser, propagating energy through an optical train, and performing outgoing wavefront sensing for wavefront correction. The latter will concentrate on maintenance of structural, wavefront, and jitter control in a simulated space high power and slewing disturbance environment.

3.3 Complementary Space Experiment

CSE is a low power space experiment that has been proposed by the Zenith Star team, and it has been suggested that a similar experiment might take place known as the Space Laser Experiment (SLE). For the purposes of this discussion, these are considered to be equivalent and to be intended to reduce space environment risks for a HEL system. The proposed CSE influenced a part of the direction of SPICE Subtask 02-05 and is therefore briefly discussed here.

The CSE would involve launching a relatively low power laser system, perhaps in the 50 KW range. The primary mirror of its beam expander would be smaller than LAMP, with a diameter of 80 cm having been proposed. Test objects would be launched from the CSE itself to test target acquisition, pointing, and tracking subsystems on nearby objects. Target range would not be an issue in a CSE. A drawing of one possible system of this type that was designed to be launched with a Delta rocket is shown in Figure 3.3.1. The advantages and limitations of such a system in reducing risk for a larger space laser system are obvious. It is less complex than many proposed space laser systems, but a CSE will still break new ground and will therefore have risks associated with it. As is discussed in Section 5, SPICE is flexible enough to address risk reduction of a CSE as well as of a Zenith Star, and such considerations have been included in this subtask.

1	Demonstrate that a high-power laser beam can be propagated through a LAMP beam expander
2	Demonstrate that a good quality holographic optical element (HOE) can be applied to the LAMP mirror and that a high-power, high-reflectivity coating can be applied in conjunction with the HOE
3	Demonstrate that a high-power beam can be sampled by a HOE placed on the LAMP mirror and that the resulting spots are of good quality and form a stable and repeatable pattern
4	Demonstrate that an OWS transfer lens can form a stable pattern of spots at the planned location of a linear-scanned area by observing the spots with an infrared staring array
5	Demonstrate that the boresight between the Alpha laser and the LAMP alignment Annulus Assembly can be aligned and maintained by a sufficiently stable ALI facility
6	Demonstrate that the LAMP mirror can be maintained as a good quality optical surface during irradiation by the high-power laser
7	Demonstrate that the high-power beam from Alpha can be corrected by the beam control transfer system (wavefront, jitter, and boresight) to a quality consistent with ALI error budgets
8	Demonstrate that the OWS system can be installed and that the OWS confirms that the outgoing beam is of a quality consistent with the ALI error budgets
9	Demonstrate that the complete optical system, from the Alpha resonator through the LAMP mirror, can be remotely aligned and calibrated consistent with the ALI error budgets
10	Demonstrate that the full-beam control system can be operated based on information obtained from the OWS system, and that wavefront error and jitter are maintained within limits specified by ALI error budgets
11	Demonstrate high-power operation of a quadrapod beam expander and demonstrate system quality consistent with ALI error budgets
12	Demonstrate beam-walk control on the primary mirror
13	Demonstrate low secondary mirror jitter consistent with ALI error budgets
14	Demonstrate LAMP segment absolute phasing under high power

Table 3.2.1. Goals of ALI

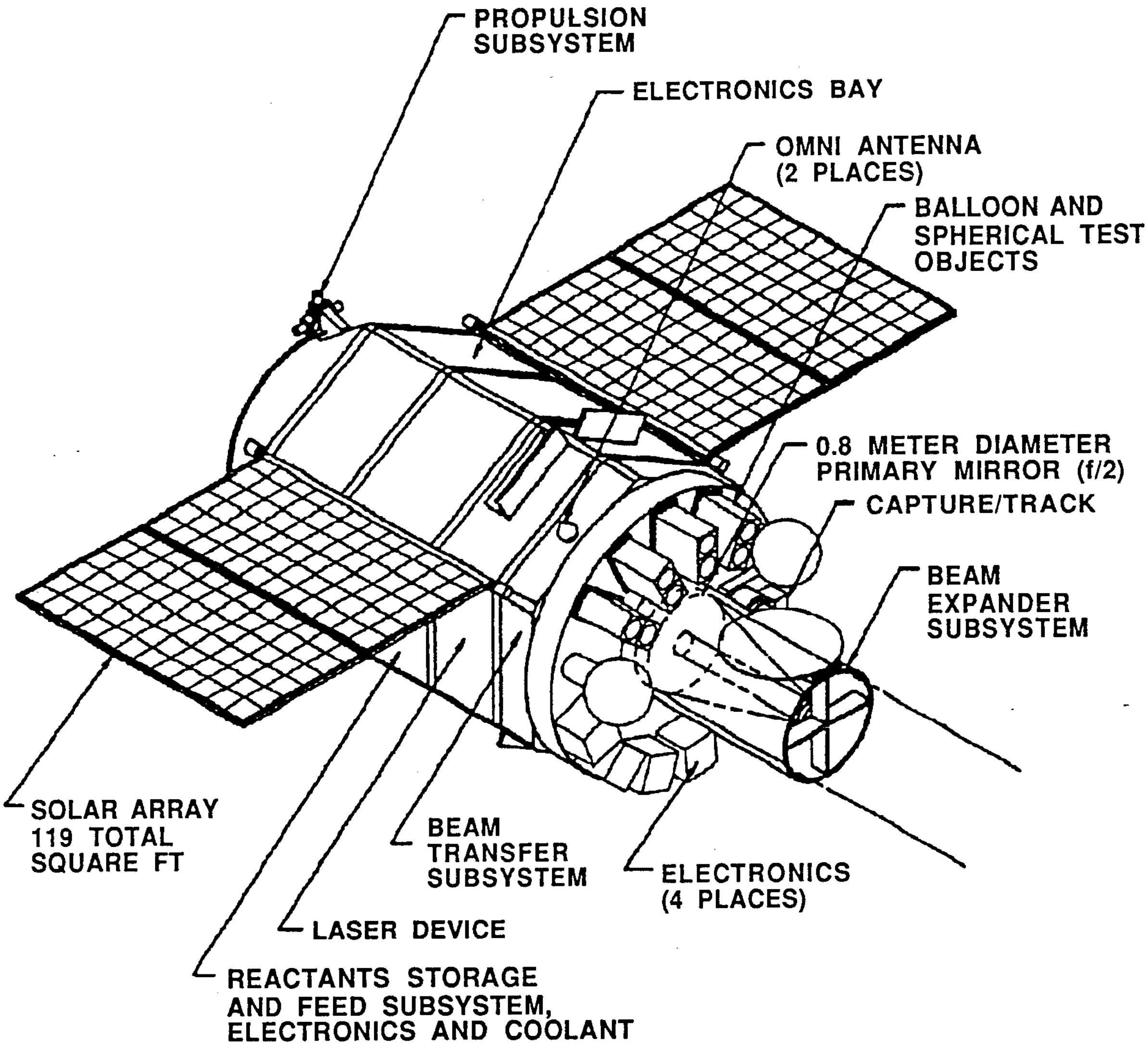


Figure 3.3.1. Complementary Space Experiment Vehicle

4.0 SPICE ZENITH STAR SUPPORT EXPERIMENT DESIGN SUBTASK

4.1 Subtask Description

Requirements of the subtask contained in the Statement of Work (SOW) are presented in this section.

The objective of the Zenith Star Support Experiment Design Subtask of SPICE is to provide the analyses required to identify, assess, and design experiments to support the Zenith Star Program using the SPICE facilities. Effort is directed toward defining experiments to determine and optimize the optical pointing and wavefront quality of:

- The Zenith Star ALI Experiment
- The Zenith Star CSE
- The Zenith Star Space Experiment

Each experiment definition must include:

- An assessment of its effectiveness to support the Zenith Star Program
- A conceptual-level experiment design
- Cost and schedule estimates
- A determination of adequacy of SPICE facilities for the experiment
- Additional hardware & facilities required for the experiment

In addition, consideration is to be given to use of existing ALI and CSE hardware in the proposed experiments.

Conceptual designs of experiments must be presented in four specified areas, although concepts that do not fit into these categories may also be included. It is required that experiments be designed to:

- Determine and compare the the improvements in line of sight stability and wavefront quality with the use of passive or active *isolation* between the laser device and the beam director,
- Assess the performance of precision *pointing and tracking* systems being considered and developed for the Zenith Star Experiments,
- Demonstrate the benefits of the use of *advanced materials* on the Zenith Star Experiments,
- Provide information for *disturbance characterization*, determination of parameter sensitivities, and disturbance model/simulation validation; this refers particularly to disturbance caused by coolant flow in the secondary mirror.

The italicized phrases are used to refer to the experiment categories in later sections of this report.

4.2 Approach to the Subtask

The Statement of Work requirements were flowed down to work assignments during a three-day integration meeting held at Lockheed, Sunnyvale. Attendance at that meeting included the SPICE program manager, all members of the Subtask 02-05 team, and several members of the Zenith Star Program staff. Additional Zenith Star personnel provided briefings on specific aspects of that program.

Participants proposed various experiments to be performed on the SPICE apparatus in support of the Zenith Star Program. Discussion produced a series of consensus decisions on the applicability of the proposed experiments in each SPICE 02-05 task area to the needs of each of the three Zenith Star experiments. As discussions proceeded, an applicability matrix evolved, finally reaching the form shown in Table 4.2.1.

	ALI	CSE/SLE	Zenith Star Flight Exp.
Active and Passive Isolation	O - no active isolation X - passive (mirror mounting) - acoustic disturbance	O - no active isolation X - passive beam expander isolation	X - active - further SAVI research O - passive - generic questions are already in SPICE
Pointing and Tracking Control • active structural control • retargeting, tracking, pointing	X - actuated mirror segments on flexible structure X - primary/secondary sensor dynamic range, bandwidth	O - no active structure O - no pointing requirements	X - slewing effects X - tracker - pointer alignment, structural effects X - smart struts
Advanced Materials and Passive Damping	← apply to all three experiments → X - advanced materials for primary mirror segment backup structure X - passive damping of tripod modes X - passive damping of mirror mount modes		
Coolant Flow Disturbance Characterization	X - admittance modeling on passive structure	O - no coolant	X - admittance modeling on passive structure X - admittance modeling on active structure X - fluid dynamics modeling

X = task area/Zenith Star experiment match. O = no task area/Zenith Star experiment match

Table 4.2.1. SPICE task area/Zenith Star experiment applicability matrix.

Each 'X' symbol in Table 4.2.1 became an effort that was assigned to a member of the Subtask 02-05 team to be developed into an experiment conceptual design. There are 14 such efforts in the table ("admittance modeling on passive structure" appears twice), with at least three in each task area. To insure that all requirements of the Statement of Work are met, a writing outline (see Table 4.2.2) was provided to the team members. The Statement of Work requirement that each experiment conceptual design be

assessed as to its applicability to Zenith Star is not addressed in the writing outline. It was decided that the assessment could best be performed by Zenith Star management. The results of the evaluation of the applicability of the experiment conceptual designs performed by the Zenith Star Assistant Program Manager/Technical are presented in Section 6.

A.	TITLE
B.	OBJECTIVE
C.	ZENITH STAR REQUIREMENT
D.	FLOW-DOWN TO SPICE
E.	CONCEPTUAL DESIGN
F.	DETERMINATION OF SPICE ADEQUACY
G.	ADDITIONAL HARDWARE/SOFTWARE/FACILITIES
H.	COST ESTIMATES
I.	SCHEDULE ESTIMATES
J	BENEFITS TO ZENITH STAR

Table 4.2.2. Experiment Conceptual Design Writing Outline.

5.0 ZENITH STAR SUPPORT EXPERIMENT CONCEPTUAL DESIGNS

This section presents the technical output of the SPICE Subtask 02-05, namely, conceptual designs of experiments to be performed in the SPICE facility in support of the Zenith Star Program. The level of detail is not uniform in this section. Some of the proposed experiments are presented in considerably more detail than is usual for conceptual designs. For example consider Section 5.1.3, Further SAVI Research. The concepts presented therein were generated during this brief subtask, but they incorporate the thinking of the technical leader of the SAVI investigations for several years as he and his team actually worked with the SAVI apparatus. The level of detail available in that area therefore is far greater than that in most other areas and, although it is believed to be beyond what is actually required here, it is included to provide maximum information to the reader.

As noted in Section 4.1, this subtask was required to generate experiment conceptual designs in four categories:

- Isolation
- Pointing and Tracking Control
- Advanced Materials and Passive Damping
- Disturbance Characterization

These are contained in the following four subsections.

5.1 Isolation Experiments

This section presents conceptual designs of the following experiments in the areas of passive and active isolation of components from vibrational disturbances:

- Passive isolation of an space based laser (SBL) component: Investigation of specific techniques for isolating, e.g., a beam transfer assembly from a spacecraft.
- Isolation of a beam expander: Techniques less extensive than SAVI that could be required in a smaller space experiment such as CSE or SLE.
- Further SAVI research: Continued investigation and upgrading of the active isolation method that has already been selected for the Zenith Star flight experiment.

5.1.1 Passive Isolation of an SBL Component

5.1.1.1 Objective

The objective of this experiment is to develop a data base and models in the area of passive isolation as applied to a gain generator assembly or a beam control transfer system to provide quantitative information for Zenith Star disturbance suppression tradeoffs.

5.1.1.2 Zenith Star Requirement

The Zenith Star Program, in an eventual full scale flight experiment, is expected to require some means of isolation between either or both of the gain generator assembly and beam control transfer system and the spacecraft. This type of design was selected by the Lockheed/Martin team previously but detailed trades remain to be performed on the exact type and placement of the devices. Due to the lack of detailed data on the vibrations to be expected from the laser device, specific requirements for isolation do not yet exist. However, in preliminary analyses, techniques have been used such as simply attenuating all vibrations by some amount (such as 60 dB) across the isolator interface. No mechanical isolator can provide this type of behavior independent of the spectral content of the vibration, therefore the conclusions of these preliminary analyses may be incorrect or may depend upon a device that cannot be built. The Zenith Star requirement is thus a generic need for fundamental information to support a future trade study.

5.1.1.3 Flow-Down to SPICE

The SPICE contractor team includes experts in passive isolation whose approaches cover a broad range of technologies in both viscous and viscoelastic techniques. As a result, the requirement for generic information on isolation technology logically flows to SPICE.

5.1.1.4 Conceptual Design

The experiment proposed should not be performed on the the SPICE structure, as it is primarily intended as a study of component-level isolation. These tests would yield more meaningful results in the controlled environment of a test bench. The proposed effort will consist of the following steps:

1. Design the experiments, their test setups, and test fixtures.
2. Procure, fabricate, and instrument the test setup.
3. Characterize the forward and reverse transmissibility of vibrations across the isolation interface. Forward transmissibility is applicable to isolation of the beam control transfer system component from the vibrating vehicle. Reverse transmissibility is applicable to the isolation of a component such as the gain generator assembly, which is itself the vibration source, and needs to minimally disturb the rest of the vehicle. This characterization includes spectral effects, and measurements of performance in various body axes.
4. Repeat some of the tests above with alternate mounting geometries for the isolators. Study the influence this has on body-space isolation performance.
5. Perform analyses which compare with the laboratory results and are able to predict how the characteristics of an individual isolator will flow to body-space isolation for a given attachment geometry.
6. Research other types of isolators than the ones tested in the experiments above, and perform single-axis mechanical impedance tests if necessary, so as to tabulate the characteristics of various types of isolators.
7. Develop useful information on how to select an appropriate mounting geometry given body-space requirements and the characteristics of the isolator device.
8. Analyze the effects of a low break-frequency suspension that such an isolation device will have on restricting the maneuverability of the host vehicle.
9. Prepare a final report that is intended as a guide to the Zenith Star engineers who must trade, select, and model passive component isolation systems. This guide will place at these engineers' fingertips a large body of knowledge supported by lab data which describes various technologies and their pros and cons, how to apply them to the six degree-of-freedom body-space isolation

problem, what their limitations are, and how to correctly model them and predict their performance in the intended application.

5.1.1.5 Determination of SPICE Adequacy

The SPICE apparatus is primarily designed to study issues related to the interface between the beam expander and the rest of the vehicle, therefore it will not be used in this experiment. (However, the plan is still to conduct the experiments in Kirtland Air Force Base Building 765 on a test bench.) The adequacy of SPICE to this task is assessed more by considering the team of isolation specialists that are currently involved in the SPICE effort. This is an excellent team to address this task.

5.1.1.6 Additional Hardware/Software/Facilities

Hardware items that are required for these experiments that are not currently included in the inventory of the SPICE facility are:

1. A set of six passive isolators, sized suitably for use as component isolators. Since the experiment will be designed around them, their sizing can cover a wide range and hardware should be available from other programs.
2. Test fixtures including a dummy component, a vibration source, mechanical mounts, instrumentation, etc. as necessary to achieve the goals of the tests described above.

5.1.1.7 Cost Estimates

The effort associated with the design and manufacture of the passive isolators themselves has not been included in this estimate. It is felt that because this experiment can be designed around a wide range of isolator sizes, existing hardware should be useable. It is therefore assumed that the isolators will be provided by the Government from another program.

Study Effort: Passive Isolation of an SBL Component	$451 K

5.1.1.8 Schedule Estimates

Figure 5.1.1.8 shows a 35-week study which should include sufficient time for all the tests and analysis described herein.

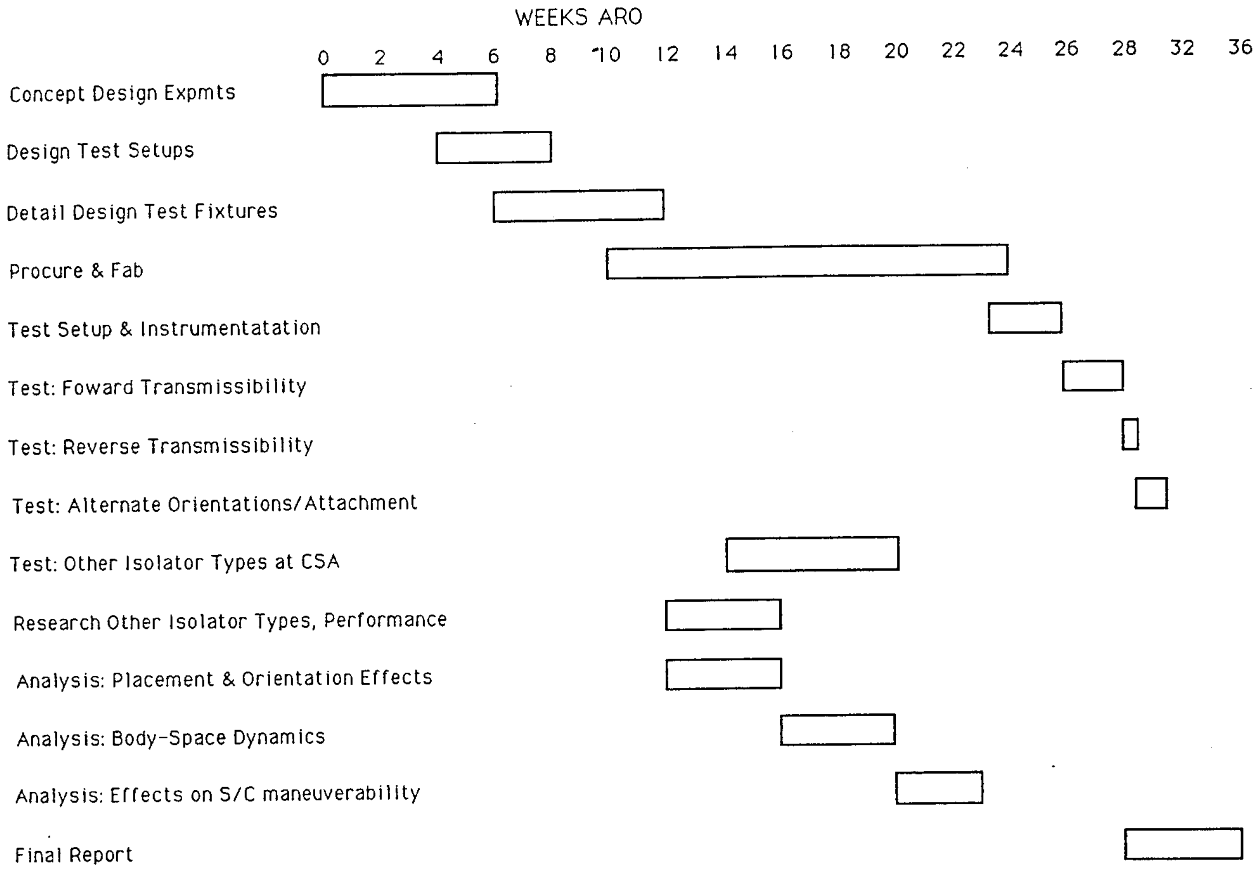


Figure 5.1.1.1 Schedule for Space Based Laser Component Passive Isolation

5.1.1.9 Benefits to Zenith Star

The Zenith Star Program, in an eventual full scale flight experiment, is expected to require some means of isolation between the spacecraft and either or both of the gain generator assembly and beam control transfer system. This type of design was selected by the Lockheed/Martin team previously, however, detailed trades remain to be performed on the exact type and placement of the devices.

This effort would allow experts in the isolation field to collect in one place data and information which would be needed by Zenith Star engineers in a future trade study. A report would be prepared which describes various technologies and their pros and cons, how to apply them to the six degree-of-freedom body-space isolation problem, what their limitations are, and how to correctly model them and predict their performance in the intended application. This effort can go on in parallel with the other Zenith Star efforts so that it will be ready when needed.

5.1.2 Isolation of a Beam Expander

5.1.2.1 Objective

The objective of this experiment is to investigate active and passive isolation technologies less complex than SAVI for application to the interface between the spacecraft and the beam expander in a CSE or scaled up CSE experiment.

5.1.2.2 Zenith Star Requirement

The Zenith Star Program, in an eventual full scale flight experiment, is expected to use isolation at the beam expander interface. The active system required there has been studied in some depth by the Zenith Star team, and the specific requirements for that system are discussed in Section 5.1.3 of this report. The ongoing Zenith Star activities of ALI and CSE do not require isolation because they either use a low power device, or have earth ground to attenuate vibrational disturbances.

Should the SLE evolve to a higher power laser than currently expected, or contain other vibration sources which are larger than expected, a cost-effective solution to disturbance issues may be sought with little time for fundamental engineering and research. Because the SLE or CSE will probably point at still targets, options for either passive or active isolation exist. The Zenith Star requirement is thus a generic need for fundamental information to support a future trade study.

5.1.2.3 Flow-Down to SPICE

The SPICE facility, with the now functioning SAVI equipment in place, provides one of the best places in the country for the study of active isolation of a beam expander in six degrees of freedom. Furthermore, the SPICE contractor team includes experts in both the passive and active isolation fields. As a result, the requirement for generic information on isolation technology logically flows to SPICE.

5.1.2.4 Conceptual Design

The proposed experiment will consist of the following steps:

1. Design the experiments to be performed, the test setup, and test fixtures. Procure and fabricate all necessary interface hardware.
2. Select the passive isolators to be used, or design and manufacture them. (See option discussed in the section on cost estimates)

3. Use the SAVI active isolation system to take data on the transmission of noise from the aft body to the beam expander. Line of sight and wavefront quality will be judged by the SPICE OSS.
4. Remove the SAVI magnetic actuators and replace them with a suitable set of passive isolators, and repeat the tests. Two different sets of passive isolators using two different passive technologies will be tested, probably based on viscous and viscoelastic techniques.
5. Reinstall the SAVI magnetic actuators and check out the system alignment.
6. Reduce data from the above experiments and compare results to analytical results.
7. Prepare a final report that describes the various technologies, their pros and cons, and the performance they are capable of achieving. This document will be written in such a way as to be of maximum value to a Zenith Star engineer responsible for a rapid trade leading to the selection of an isolator system in the event it should become necessary. The information needed for such a trade will be anticipated and presented in a cohesive manner.

5.1.2.5 Determination of SPICE Adequacy

The nature of this experiment makes the SPICE apparatus a logical choice for the effort. The government has consigned the residual hardware of the SAVI program to SPICE, and it provides this experiment with the testbed, beam expander, and active isolation system already in place.

5.1.2.6 Additional Hardware/Software/Facilities

Additional hardware will be required for these experiments which is not currently included in the inventory of the SPICE facility, namely:

1. A set of six viscous passive isolators, sized appropriately for these experiments.
2. A set of six viscoelastic passive isolators, sized appropriately for these experiments.
3. Interface hardware necessary to mount the passive isolators to the current interface surfaces where the magnetic actuators are located.

5.1.2.7 Cost Estimates

The cost estimate is separated into two pieces for this effort. The effort associated with the design and manufacture of the passive isolators themselves is such a large part of the total that it has been broken out. This provides the Government with the option of providing passive isolators, which might be available from another program.

1. All effort excluding design and fabrication of passive isolators $336 K
2. Design and fabrication of passive isolators <u>$515 K</u>

   Total, if Government furnished isolators unavailable $851 K

5.1.2.8 Schedule Estimates

Figure 5.1.2.8 shows a 30-week study which should include sufficient time to design and fabricate the isolators. Should the isolators be available from another Government program, approximately six weeks of this schedule could be removed from the "procure and fabrication" line.

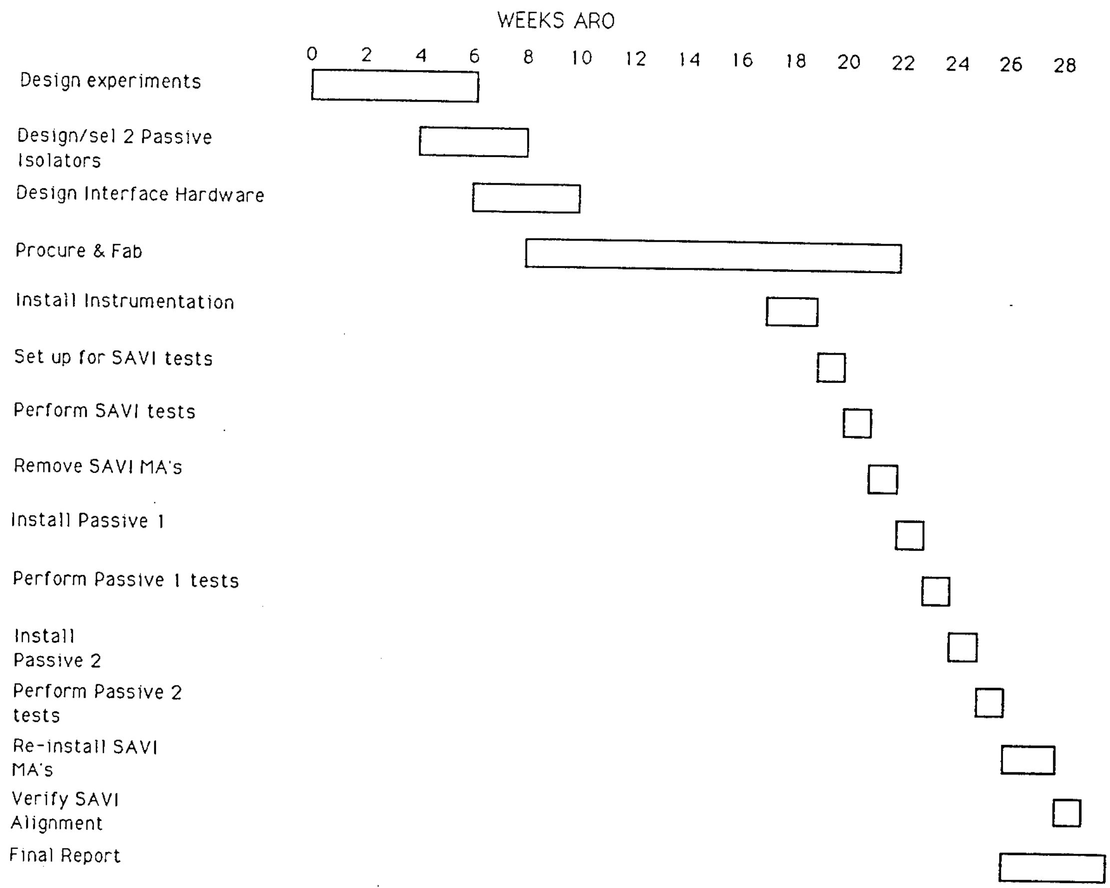


Figure 5.1.2.1 Schedule for Beam Expander Isolation

5.1.2.9 Benefits to Zenith Star

The ongoing Zenith Star activities of ALI and SLE do not require isolation because they either use a low power device or have earth ground to attenuate vibrational disturbances, and thus they are not considering isolation technologies. However, experience has often shown that after careful study vibrations are found to be a greater problem to optical systems than was originally estimated. Because detailed studies are necessary to make such a determination, this is typically not discovered until late in the evolution of a program. This SPICE effort would allow experts in the isolation field to collect data and information which would be needed by SLE engineers in the event that some type of isolator did become necessary in the future. It would make the needed information readily available in support of a rapid trade study to provide a cost-effective solution to a vibration problem. This effort can go on in parallel with the other Zenith Star efforts so that it will be ready if needed.

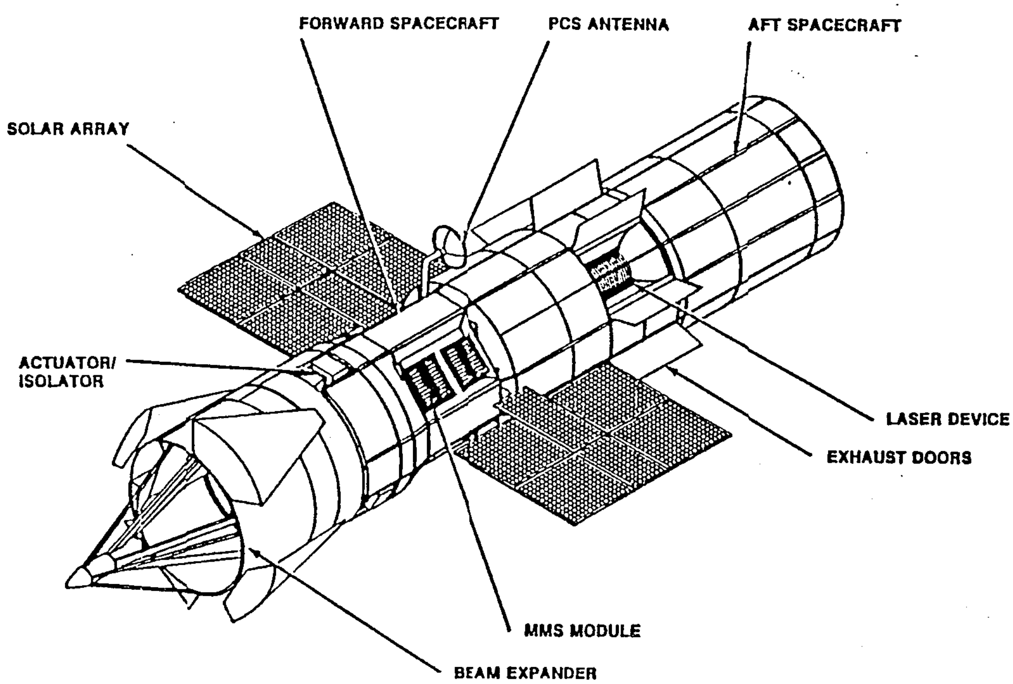


Figure 5.1.3.1 Zenith Star Space Vehicle

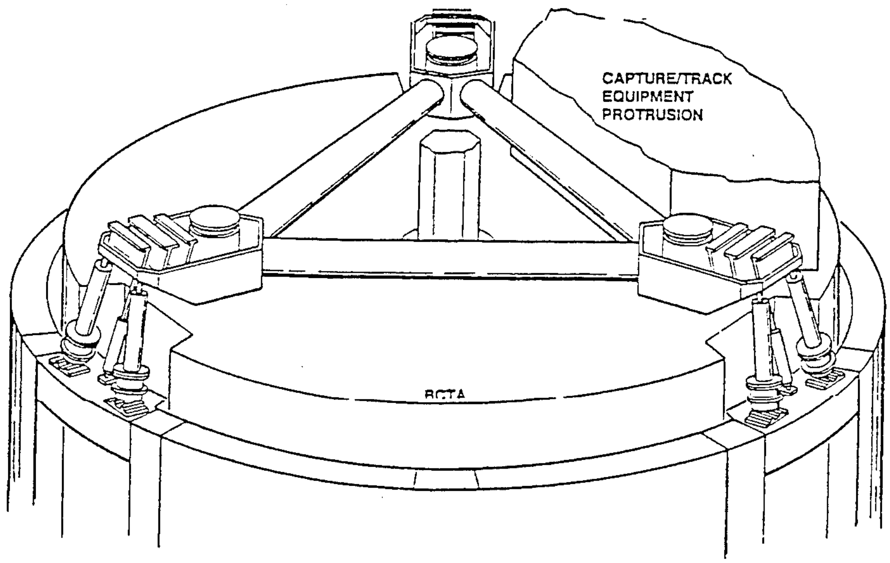


Figure 5.1.3.2 Actuator/Isolator System Hardware

5.1.3 Further SAVI Research

5.1.3.1 Objective

The objective of this experiment is to perform further technology research in the area of active magnetic isolation using the SAVI equipment as the testbed and to improve the performance of SAVI. This work will focus on anomalies observed during the original SAVI testing, identify causes and solutions, and improve measured performance when economically feasible. The goal of the effort is to utilize the Government's investment in the SAVI equipment to enhance the state of readiness of magnetic isolation technology to support a flight program.

5.1.3.2 Zenith Star Requirement

In a full scale flight experiment, the Zenith Star Program will require the use of SAVI technology. This requirement flows from the need for isolation of the beam director from the vibration of the high-power laser, and also the need to articulate the beam director relative to the rest of the spacecraft.

Figure 5.1.3.1 depicts the Zenith Star space vehicle as it was planned before the program was restructured. This represents a typical configuration for a space-based laser that might eventually be deployed. The laser device and exhaust management system are located in the aft spacecraft. After a separate launch, this system was to dock with the forward spacecraft, which was responsible for beam control and tracking. The beam expander uses cassegrain optics with a segmented, active primary mirror.

To deliver the maximum energy to the target, precise control of the beam expander optics is required. The figure of the primary mirror must be maintained to tight tolerances and excitation of structural modes must be minimized to insure that the emitted radiation has a uniform wavefront and minimal jitter.

Turbulent chemical reactions and exhaust gas management from the laser source result in significant broadband vibration of the vehicle, which conflicts with the precise control requirement of large optics. The resolution of this inconsistency results in the requirement for mechanical isolation between the laser source and the beam expander optics. Such isolation must be present in six degrees of freedom, and must extend over a wide frequency spectrum. To accommodate this requirement, the vehicle is broken into two halves, just behind the beam expander. Clearly, if control were possible, optimal isolation would be achieved by making the beam expander a separate free-flyer which made no contact with the aft body. To effect control, an isolator is placed between these two bodies which approximates pure isolation while minimizing long-term differential motion. A simple example of a pure (passive) isolator would be a set of well-damped weak springs, such that the low-frequency motions are passed and higher-frequency motions are rejected.

The fact that pointing and tracking must be achieved is inconsistent with the concept of the simple passive isolator. If the isolator is designed to pass only low frequency motion, an attempt to quickly reorient the spacecraft would simply result in the springs bottoming out. This inconsistency requires the use of an active isolation technique that is capable of passing certain desired and deterministic motions which are well outside its operating passband. Clearly, the requirement to be (effectively) very soft for random inputs and very stiff for specified deterministic inputs in the same frequency band at the same time places stringent requirements on the dynamic range of the isolator, and points toward the need for a state-of-the-art device.

During the previous Zenith Star Program, specific requirements were identified for the beam director isolation/articulation system, referred to as the Actuator/Isolator . These requirements are shown in Table 5.1.3.1.

5.1.3.3 Flow-Down to SPICE

During the previous Zenith Star Program, a trade study was performed by Martin Marietta in which the SAVI technology was chosen as the baseline for beam expander isolation. Honeywell was awarded a subcontract to develop a Zenith Star design, and Figure 5.1.3.2 shows the configuration which was selected at that time.

Requirement	Current Spec.
Articulation (at pivot point)	
Rotation about y or z	± 3 deg
Rotation about x	± 1/2 deg
Translation, all axes	±25 mm
Isolation (1 - 200 Hz)	-60 db
Control Actions (beam expander, at pivot)	
Angular acceleration, y or z	± 40 mrad/s^2
Angular acceleration, x	± 3 mrad/s^2
Angular rate, y or z	± 50 mrad/s
Angular rate, x	± 10 mrad/s
Translation rate, y or z	± 100 mm/s
Translation rate, x	± 10 mm/s
Beam Expander Mass Properties	
Mass	8150 kg
Inertia (y or z through beam expander center of mass)	34,500 kg-m^2
Center of mass offset, beam expander center of mass to pivot	2.31 m
Precision	
Control action accuracy	±3% of full scale
Beam expander position readout accuracy	
Translation, any axis	±0.4 mm
Rotation, any axis	±0.5 mrad
Control action granularity	
Forces	±1 N
Torques	±4 N-m
Actuator/Isolator induced beam expander jitter, quiescent	0.1 µrad

Table 5.1.3.1 Actuator/Isolator system requirements.

One of the things that made the SAVI technology particularly attractive to the Government was the fact that the SAVI program was already funded and due to produce laboratory data in time to support Zenith

Star. The intention was to identify any problems in this equipment, and immediately take corrective actions to insure the success of the Zenith Star design.

While the SAVI program was a success overall, areas have been identified in which further development is justified in support of an evolutionary Zenith Star flight. Unfortunately, the requirements for an isolation system are minimal for the SLE program, therefore this critical technology development runs the risk of being overlooked.

This technology development can be pursued in parallel under the SPICE program, using the residual equipment from the SAVI program as a testbed. Since the Zenith Star Actuator/Isolator design descended directly from SAVI, the testbed is directly traceable and applicable to a Zenith Star risk reduction effort.

5.1.3.4 Conceptual Design

This section describes the nature of several efforts that could be performed. These are presented in logical groups which could be authorized separately if desired. However, all are recommended, and there are economies in performing them simultaneously which have been assumed in the estimates shown in later sections.

1. SAVI "Loose Ends": This effort will address several of the things which were identified by both Honeywell and the Government as desirable if the SAVI hardware were to be used further, although they were not deemed necessary to complete the SAVI program itself. Most of these are directed towards protecting the hardware from damage during use.

Software will be added in the 5 Hertz frame which computes the angles of the linear actuators with respect to the intermediate gimbal structure, and compares these angles to the operating envelope as a means of identifying a shutdown condition. The current linear actuator limit switches do not protect the equipment from a contact between the a linear actuator and the intermediate gimbal structure resulting from various combinations of compound angles, and several close calls have already occurred during SAVI experiments. Costly damage to the linear variable differential transducers and the linear actuators could result from something as trivial as a manual disturbance during a demonstration.

The linear actuator limit switches will all be placed back into service. Several of these were damaged during the "close calls" referenced in the previous paragraph. While the limit switches are not sufficient to

prevent linear actuator/intermediate gimbal structure contact, they are still important to prevent linear actuator overextension in the event of a severe failure.

The fault sense electronics which already exists will be placed back into full service. Several of the fault sense functions are currently disabled due to last-minute changes to the hardware which were not incorporated.

During the SAVI data reduction, small errors in the present control software were uncovered in the areas of linear actuator nonlinearity compensation and center of gravity location. These will be fixed. In addition, a thorough review of the software changes which were made during system integration will be performed to insure no other errors exist.

Several pieces of separate "test software" were developed during the system integration which are necessary to repeat system-level calibrations. These are difficult to identify, and are not currently subject to any kind of configuration control. These pieces of test software will be formally included in the SAVI control software, and their functions will be made available as options which can be invoked at run-time.

The only currently outstanding malfunction in the SAVI electronics is an intermittent problem with the sample-and-hold circuits which hold the software command outputs at each vertex. When one of these intermittent errors occurs, a brief force transient appears on one of the system actuators and disturbs the beam expander. The problem will be located and corrected.

2. Isolation Performance / Quiescent Noise: This group of investigations will lead to improved performance of the system as seen in the line-of-sight stability of the beam expander. These efforts will demonstrate improved performance on the SAVI hardware if economically feasible, or may only specify design changes which will enhance performance of the flight article when built. These investigations will address all beam expander disturbances from the SAVI equipment, whether passed from the aft body, passed from intermediate gimbal structure quiescent motion, or applied directly by magnetic actuator force loop noise.

Quiescent noise of the SAVI system was measured to be significantly higher than expected based on previous experience, and it is important to discover the reason for this to insure that noise is not a factor for an evolutionary flight program. The SAVI data which showed excessive quiescent noise will be repeated with additional instrumentation and the system configuration will be changed in increments as necessary to pinpoint the source of the noise and its mechanism for reaching the beam expander. Once this is understood, corrective actions will be determined. The possibilities which have been identified so far are:

1- intermediate gimbal structure limit cycle motion could be coupling through the magnetic actuators. If the intermediate gimbal structure motion is the source, this can be determined by temporarily shutting off the linear actuators. All of the SAVI data was taken with the follow-up running, so this determination cannot be made with the existing data.

2- Magnetic actuator quiescent noise could be higher than expected. There is no precedent for this, but the possibility will be checked. In the absolute worst case, a modification of the magnetic actuator flux-squared loop design might be necessary.

3- Ambient air turbulence disturbances might be amplified by the SAVI actuators due to gap compensation errors. This is also unprecedented, but possible. Gap compensation errors will be addressed in the next paragraph whether or not this is determined to be a factor in the quiescent noise problem.

Magnetic actuator gap compensation was discussed in detail in the SAVI final report. This is a critical calibration in determining isolation performance, and the calibration obtained was not as good as experience has shown to be possible. The most likely reason for this is the fact that the calibration data was taken at the system level instead of on a bench test fixture for each actuator, and thus was of a lesser quality. However, it is also possible that a repeatability problem exists in the calibration for reasons which could range from temperature sensitivity to a bad connection. This will be explored in detail to see why the calibration quality did not live up to our prior experience, and preventative measures will be suggested for how to insure a good and stable calibration in a flight system.

During early system integration, when the beam expander position loops were off-nominal and had less margin, it was noted that vertex number two would occasionally break into a low frequency oscillation. No formal data was taken on this, and no reason was ever uncovered to explain why this vertex should always be the first one to do so, and never the others. This will be looked into further to see if this was actually a symptom of a problem which might be compounding one of the others being studied.

The magnetic actuator coil drivers are pulse-width modulators, and experience a nonlinearity near zero duty cycle when the flyback diodes can fully discharge the coil current within the period of the modulator. This is normal for this type of driver, and a bias flux was planned for both coils of an actuator to avoid the nonlinearity. However, during integration, it was found necessary to set the bias flux levels higher than originally expected, thus degrading quiescent isolation by approximately 6 db. This will be explored in more detail and a modification to the driver design may result.

After these studies, if any design modifications are cost effective enough to be performed immediately on SAVI, they will be performed and the isolation/noise measurements will be repeated to document the improvement.

<u>3. Follow-up System - Linear Actuator Characterization and Compensation</u>: This activity may turn out to be coupled with the work on quiescent noise, as it is known that the current follow-up system exhibits a slight limit cycle during quiescent periods and this may be a disturbance source. It is also coupled into isolation performance due to the fact that the follow-up dead band eliminates the low frequency disturbance attenuation which was intended, at least for low amplitudes.

The follow-up system integration in SAVI was made difficult by the presence of an unexpected amount of stiction and drag in the linear actuators, which necessitated software compensation. The compensation used was intended as a means to get the system working quickly, and very minimal actual characterization of the linear actuator nonlinearities was performed.

In this experiment, the linear actuators will be characterized in greater detail, and modifications to the mechanical design will be suggested which might benefit a future program. However, it is not expected that the SAVI linear actuators will be modified based on the improved characterization data; the nonlinearity compensation in software will be refined.

<u>4. Follow-up System - Alternate Control System Approach</u>: This activity may also turn out to be coupled with the work on quiescent noise, as it is known that the current follow-up system exhibits a slight limit cycle during quiescent periods and this may be a disturbance source. It is also coupled into isolation performance due to the fact that the follow-up dead band eliminates the low frequency disturbance attenuation which was intended, at least for low amplitudes.

The SAVI linear actuator mechanical design is extremely challenging due to the combined requirements for high force, high rate, long stroke, and high stiffness. Because this design is already pressing the state of the art, it is possible that the stiction/drag cannot be significantly improved without causing another design parameter to become unacceptable. In order to insure smooth, linear follow-up performance even in the presence of actuator nonlinearities, alternative control techniques will be explored. One inner loop technique that has considerable promise is based on a harmonic oscillator which generates sine and cosine current commands directly. If power were not important, one could drive the linear actuator coils at $20 \bullet \sin(\theta)$ amperes and $20 \bullet \cos(\theta)$ amperes continuously, where θ is the rotation angle of the motor. If motion were desired, phase would be changed accordingly. This type of scheme would simply overpower any and all nonlinearities of the actuator with the full torque of the motor. If no motion were desired, the

electrical phase would be held constant, and the motor would "cog" at full torque, holding the actuator very still. Of course, such a control scheme would burn up the motor in practice, and was rejected in earlier trades. However, the concept could be modified to add a gain scheduling algorithm that allows the current to be reduced whenever it is not needed. This could be implemented by driving the existing resolver backwards with sine and cosine inputs and extracting a rotational position error which could control the current gain. The alternative inner loop will be built up on separate electronics cards and simply exchanged with the existing cards for testing. In this way, the baseline SAVI hardware need not be modified, and will always be available for use in other experiments.

5. Gravity Offload center of gravity Pivot Assembly: This assembly suffered two failures during the integration, and was finally modified in a way that insured that it would not break again, but that also greatly impaired its performance. The direct consequence of this workaround was poor large-angle retargeting performance, as described in the final report. This activity will provide for the redesign (if necessary) and repair of the pivot assembly to allow it to perform as intended. After this, precision data will be taken on the beam expander center of gravity location (which could not be taken before because of the failure), the software will be recalibrated for the measured center of gravity location, and the retarget data will be repeated.

6. Aft Body Special Test Equipment: The baseline design of the aft body special test equipment called out a set of control loops which would serve to make the aft body easier to work with. These loops were intended to help keep the shakers near center stroke, and help the aft body react to the retarget torques without deflection. Problems were encountered in stabilizing these loops during the integration, and since they were related to the special test equipment and not the SAVI, they were deferred. Without them, it proved extremely difficult to do simultaneous vibration and retargeting maneuvers, and to do precision vibrations in specific degrees of freedom for diagnostic data. In this activity, the aft control system will be brought up to the originally intended baseline.

7. Simulation: As the experiments above are performed and more is learned about the SAVI hardware, the digital simulation tool which was developed during the SAVI program will be kept current and used as a diagnostic tool. Knowing what to expect from various subsystems during tests in which the hardware is configured in various ways is a tremendous help in identifying the specific subsystems that are contributing to a problem.

8. Miscellaneous Studies: This section provides a level of effort budget to perform other miscellaneous investigations which have not been specifically mentioned herein. Any activity performed under this category must be specifically approved by the customer prior to expenditure of hours.

5.1.3.5 Determination of SPICE Adequacy

The nature of this particular experiment makes the SPICE apparatus not only adequate, but essential. The Government has consigned the residual hardware of the SAVI program to SPICE. Therefore it is the only logical place at which to perform SAVI-related research. Use of any other host for these experiments would entail re-building large pieces of the SAVI equipment. The only adequacy issue to explore is whether SPICE will be available for these studies. This issue is resolved as discussed in the section on schedule below.

5.1.3.6 Additional Hardware/Software/Facilities

The descriptions of the experiments above include fabrication of several new pieces of hardware, electronics, and software as a part of the effort. In addition, the performance of these investigations will also require peripheral hardware and software to be used in the SPICE facility. The hardware will be small pieces of special test equipment. Software modifications will be performed and controlled by members of the original SAVI team, or their trained designates. Following is a list of currently defined additional hardware/software:

1. A bench test fixture capable of collecting calibration data on the magnetic actuators for the gap compensation studies.
2. Test fixtures to study temperature dependence of the magnetic actuators.
3. Test fixtures for characterizing of the linear actuator nonlinearities.
4. Modifications/additions to the aft body special test equipment necessary to effect control.
5. Additional test software to configure the system as needed for various investigations.

5.1.3.7 Cost Estimates

The experiments listed above have been broken into groups to provide the Government with flexibility in prioritizing activities. Table 5.1.3.2 shows the cost by experiment group. As stated previously, there are economies associated with performing all this work simultaneously, and these have been assumed in the estimates below.

Experiment Group	Estimate ($K)
1. General Support	180
2. SAVI "Loose Ends"	190
3. Isolation Performance / Quiescent Noise	32
4. Follow-up System - Linear Actuator Char. and Comp.	190
5. Follow-up System - Alternate Controls Approach	125
6. Gravity Offload center of gravity Pivot Assembly	108
7. Aft Body Special Test Equipment	112
8. Simulation	67
9. Miscellaneous Studies	77
Total	**$1,300K**

Table 5.1.3.2. Cost Breakout by Experiment Group

5.1.3.8 Schedule Estimates

These experiments, while vital to the evolutionary Zenith Star deployment, do little to support the near term (ALI, CSE) Zenith Star activities and thus do not have pressing deadline dates. This gives us the unique ability to fit them into the rest of the SPICE program with a minimal amount of interference and conflict in the use of the SPICE facility. For this reason, a long schedule with an unusually low level of effort is recommended for these experiments. Planning and experiment design will take place for several experiments simultaneously, along with the fabrication of any necessary special test equipment. Then, when a window of opportunity opens for the use of the SPICE facility, short, intensive efforts will take place on site in Building 765. As many of these experiments are of a technology research nature, they may be spread over several on-site visits, with off-site time in between being used to reduce data and decide what to look at next. This sporadic approach to the on-site effort also provides an additional efficiency to the Government in that the manpower used for the investigations can be shared very efficiently with other programs. Individuals working on-site will only be there when needed, and will generally have activities supporting more than one experiment.

Given this philosophy, the schedule (Figure 5.1.3.3) shows approximately how these experiments might be spread over time.

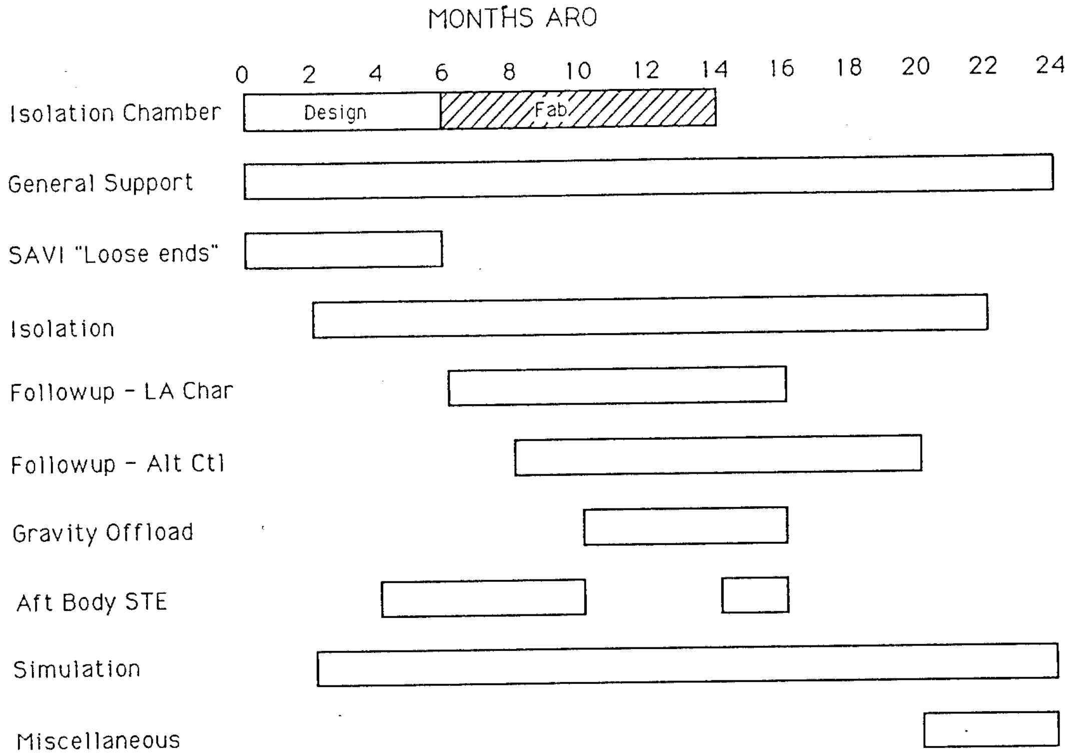


Figure 5.1.3.3 Schedule for Further SAVI Research

5.1.3.9 Benefits to Zenith Star

The SAVI magnetic isolation technology has been identified as critical to the success of an evolutionary Zenith Star (or any other space-based laser system) deployment. For this reason, the Government invested in the SAVI program, which fabricated prototype hardware using the best design techniques known in 1985, and tested the hardware. What is needed to insure flight readiness is to continue this work by learning from the SAVI experience and bringing the state of the art up to 1990. The ongoing Zenith Star activities of ALI and SLE do not require isolation because they either use a low power device or have earth ground to attenuate vibrational disturbances, and thus they are not allocating funds to continue the development of this critical technology. But the need has not gone away. This is an opportunity to carry this technology forward in a very cost-effective way, on the best possible facility, using the same team of people who did the original work. This effort can go on in parallel with the other Zenith Star efforts so that when the time comes for an HEL deployment, active isolation technology will be ready.

5.2 Pointing and Tracking Control Experiments

The conceptual designs of experiments to reduce risk on Zenith Star control systems are presented in this section. A fairly broad view of the task was taken in that concepts were considered even if similar experiments were already being contemplated elsewhere in the community. No experiment is included unless it was our view that SPICE brings something of unique value to it. This section presents discussions of the following experiment conceptual designs:

- Active control of primary mirror segments: Evaluation of active control of primary mirror segments including comparison of active control to use of the actuators in a set and hold mode.
- ALI primary mirror - secondary mirror alignment system investigation: Evaluation of the ALI low bandwidth primary mirror-secondary mirror (PM-SM) alignment system by simulating it on SPICE.
- High performance slewing of a Zenith Star beam expander surrogate: Demonstration of high performance slewing on a large beam expander with low resulting line of sight and wavefront errors.
- Separate aperture tracker effects: Investigation of aspects of the Zenith Star boresighting method and the effects of tracker mass.
- Use of smart struts in a Zenith Star beam expander surrogate: Investigation of the use of struts with internal active control as beam expander tripod legs.

5.2.1 Active Control of Primary Mirror Segments

5.2.1.1 Objectives

The objectives of this experiment are:

1. To demonstrate phasing of the segments of the SPICE primary mirror surrogate in the presence of high power disturbances by active control.
2. To compare the performance of the set and hold mode of segment actuators to use of active control.

5.2.1.2 Zenith Star Requirements

The ALI experiment has, as one of its goals, the demonstration of absolute segment phasing under high power laser radiation. The Zenith Star flight experiment has baselined a set and hold mode for the actuators on the LAMP mirror, leaving the wavefront distortion due to segment dephasing, i.e., piston offsets among the segments, to be dealt with by the deformable mirror. That is consistent with that program's calculation of about 0.03 μm RMS segment piston displacement. Because the beam reflects

from the primary, a displacement of a segment by δ produces a piston offset in the wave striking it of 2δ. If the segment pistons are zero mean gaussian random variables, the Strehl ratio is given by:

$$S_r = \left[1 + (N - 1)\exp\left\{-(2\pi\sigma / \lambda)^2\right\}\right] / N \tag{1}$$

S_r is 0.98 for wavelength (λ) = 2.7 μm, beam diameter (D) = 4.0 m, number of segments (N) = 7, and RMS segment piston (σ) = 0.06 μm. That may be too optimistic because:

1- Actual secondary mirror coolant flow disturbance may be considerably higher than that assumed in the Zenith Star calculation. Although it was based upon analysis provided by the designer of the secondary, measured values such as the Secondary Mirror Jitter Test (SMJT) data have shown forces that are 10 - 20 times as high as that analysis yields.

2- The SAVI has so far not achieved the degree of isolation of the beam expander from aft body vibration assumed in the Zenith Star analysis. It may well do so in the future but still the assumption concerning it is optimistic.

For a worst case, consider a RMS segment piston of 0.6 μm. Using the prudent design guide that the deformable mirror actuators must be able to deal with $\pm 3\sigma$ displacements, a dynamic range of ±2 μm is required. The deformable mirror may not be the location at which to deal with this source of wavefront error. It must be dealt with because, from equation (1), the Strehl from that dephasing alone is about 0.14, a value that would compromise the ability of the Zenith Star flight experiment to meet its target engagement goals. It is possible that, should the assumed optimistic values of segment dephasing not be realized, Zenith Star could require active control of the LAMP bipod actuators to achieve a reduction in RMS segment piston by a factor of as much as 10.

5.2.1.3 Flow-down to SPICE

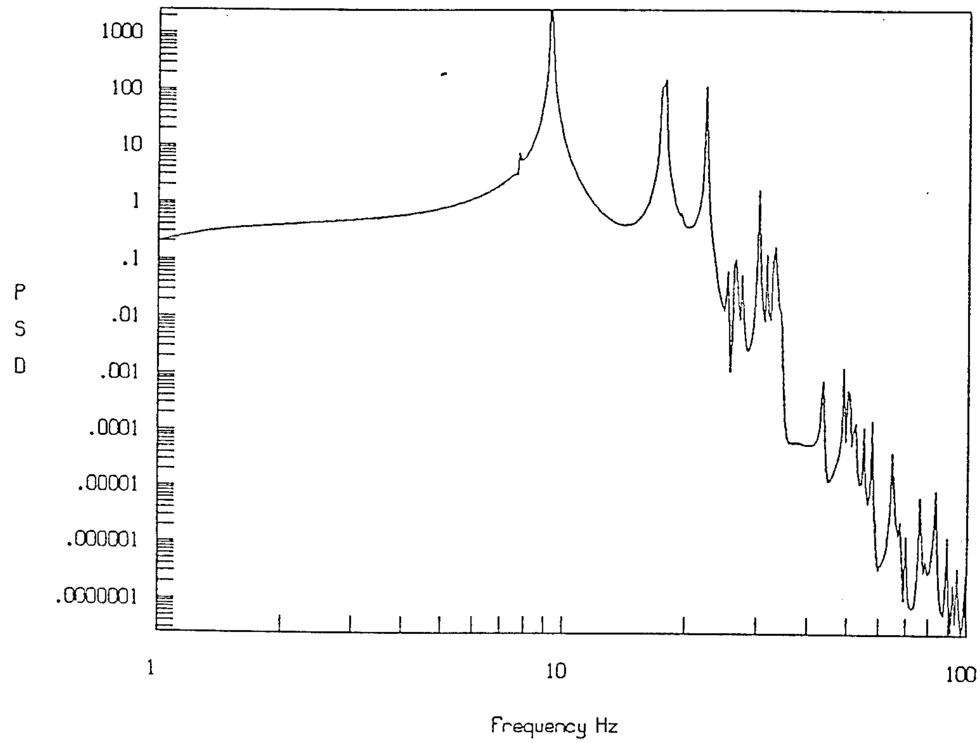
Disturbances of virtually any power spectral density can be input to the SPICE apparatus using SAVI and auxiliary means such as proof mass actuators. The ALI experiment will take place in a different environment from Zenith Star and the disturbances encountered in ALI will not be traceable to the Zenith Star flight experiment. Simulating the Zenith Star vibration environment on the SPICE apparatus will provide data that is traceable to the flight experiment. The similarity in size of the SPICE apparatus and the Zenith Star and ALI beam expanders also provides traceability (e.g., LAMP mirror diameter = 4.0 m, that of SPICE primary mirror surrogate = 5.6 m).

The SPICE OSS operates with a higher noise level than is consistent with high performance by a space based laser system. Therefore, in demonstrating line of sight and wavefront control, it is necessary to scale up the disturbances expected by the space based laser system so that disturbance rejection can be done well above the noise background. This does not reduce the usefulness of results from SPICE. The control laws used are linear. The same techniques that are used to reduce RMS segment piston from 40 μm to 4 μm would be used to reduce RMS segment piston from 0.6 μm to 0.06 μm. A final goal of 4 μm would be comfortably above the OSS gap sensor measurement capability on SPICE of about 0.3 μm.

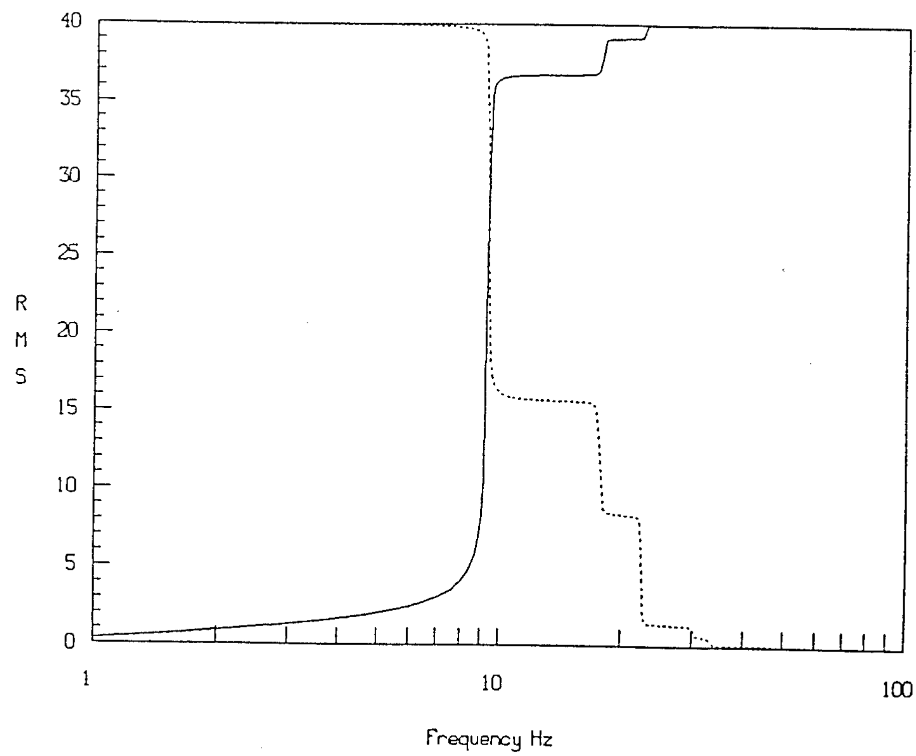
The SPICE structural model was modified to include actuators at the primary mirror surrogate attachment points rather than the rigid fasteners that now exist in the hardware. These were taken to function as 20 Hz springs in the set and hold mode. Figure 5.2.1.1a is the piston power spectral density on a typical segment that results when a scaled up version of the disturbance spectrum assumed in the design of the Zenith Star flight experiment is input to the modified SPICE structural model. Figure 5.2.1.1b shows that the scaling is such as to make the total RMS wavefront piston 40 μm.

A brief preliminary analysis was done to estimate the bandwidth that is required of a piston control servo. Figure 5.2.1.2a shows the error rejection curve for a 20 Hz closed loop simple type II servo with damping ratio (ζ) = 0.9. Application of it to the distortion spectrum of Figure 5.2.1.1a results in the residual spectrum of Figure 5.2.1.2b. The RMS residual piston is seen in Figure 5.2.1.2c to be 33 μm. Raising the bandwidth to 60 Hz results in the error rejection curve of Figure 3a. As seen in Figures 5.2.1.3b and c, the piston is reduced by a factor of about 3 to 13.5 μm by the 60 Hz control loop. Clearly, further elaboration of the control system design will be able to produce the additional factor of 3 to enable SPICE to demonstrate the techniques needed for the 10 fold segment piston reduction that Zenith Star might well require.

The problem is linear, so demonstrating reduction from 40 μm RMS piston to 4.0 μm with a scaled Zenith Star disturbance spectrum provides a reduction in risk to the performance of the Zenith Star flight experiment from primary mirror segment dephasing.



A. Segment Piston PSD From Scaled Up ZS Disturbance



B. Total RMS Wavefront Piston

Figure 5.2.1.1 Segment Piston Spectrum from Scaled-up Zenith Star Disturbance

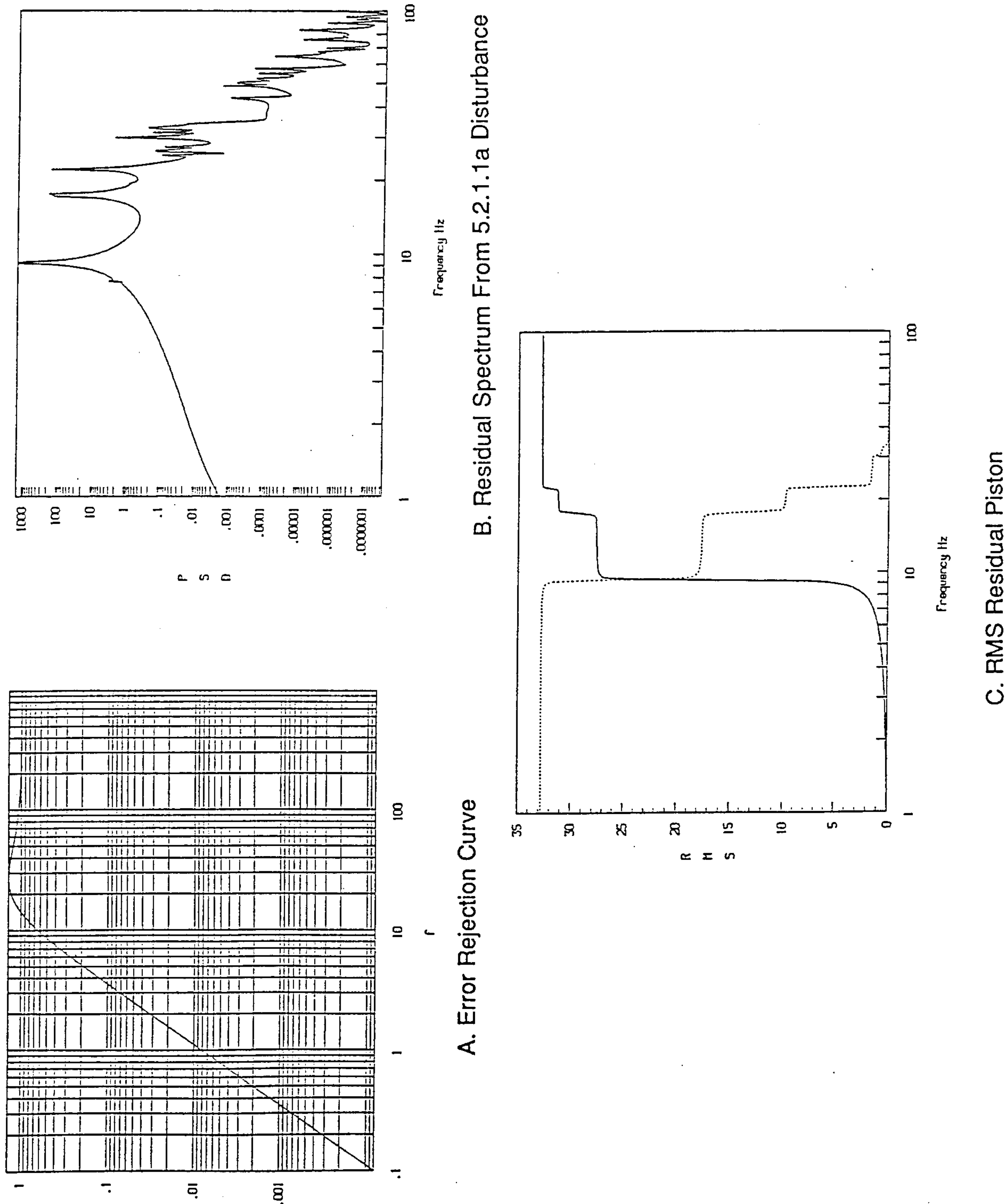


Figure 5.2.1.2 Closed Loop Simple Type II Servo, $\zeta = 0.9$, 20 Hz

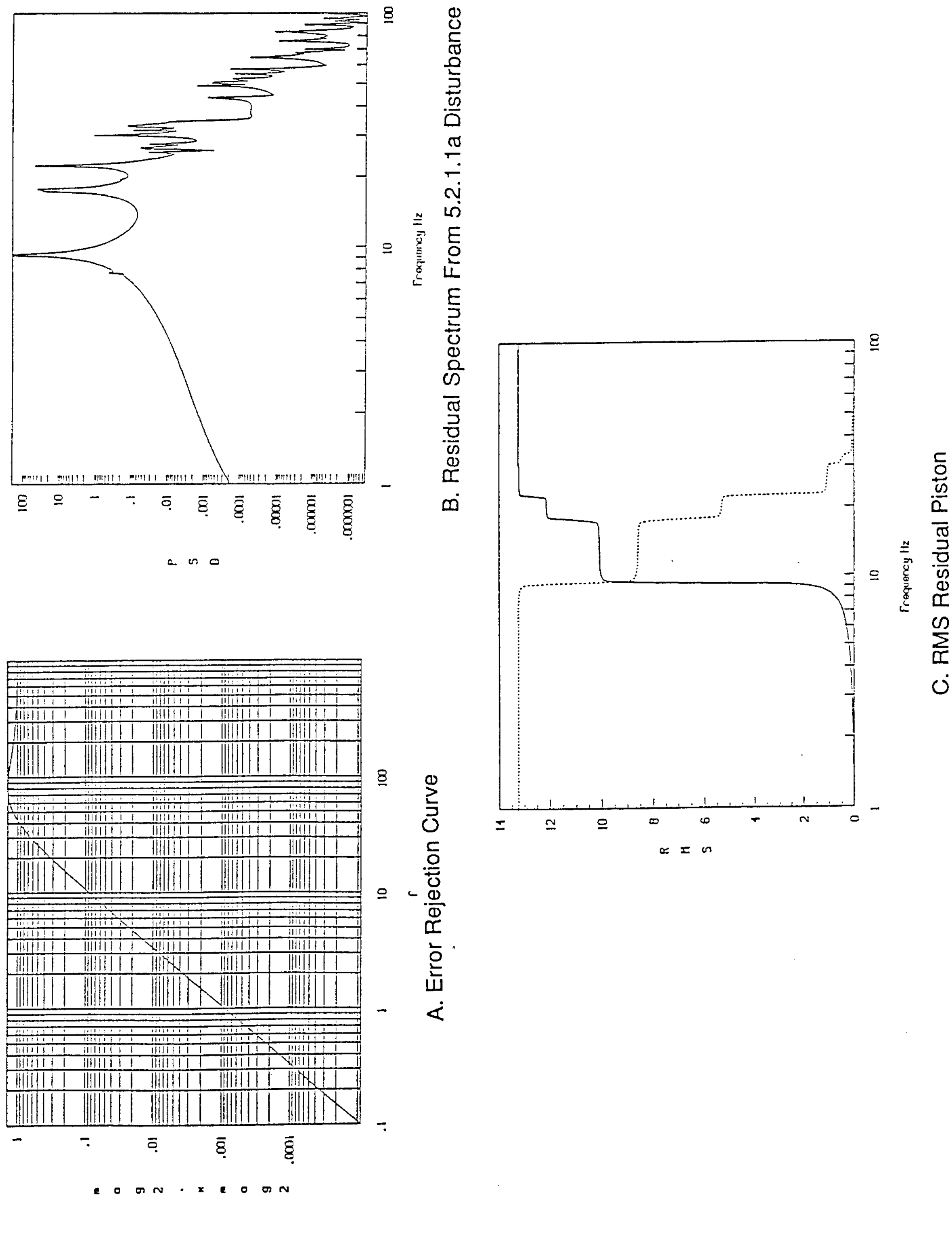


Figure 5.2.1.3 Closed Loop Simple Type II Servo, $\zeta = 0.9$, 60 Hz

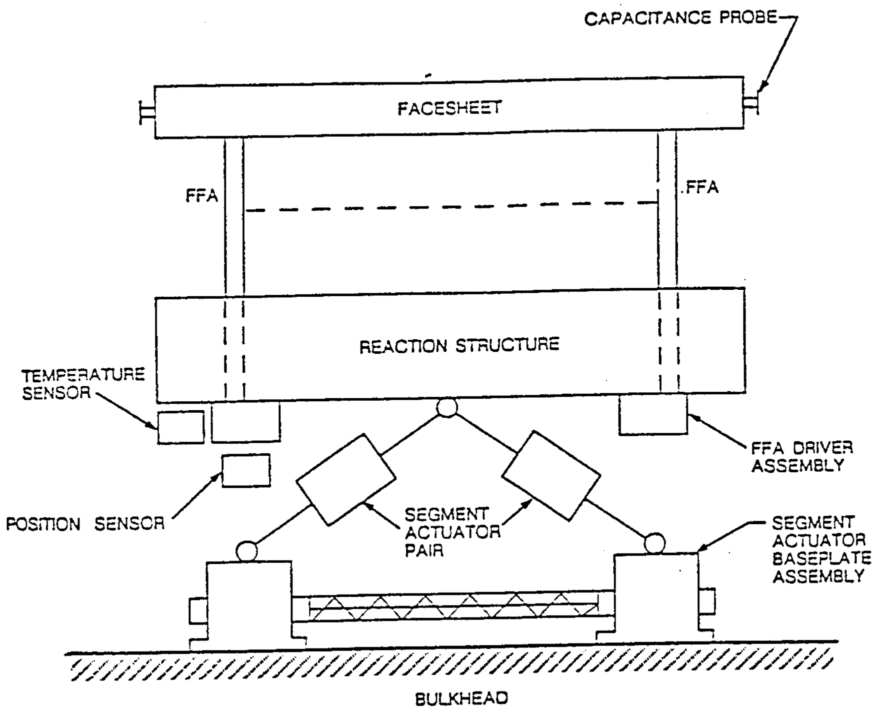


Figure 5.2.1.4 Horizontal View of Bipod Actuator Position in Control Structure

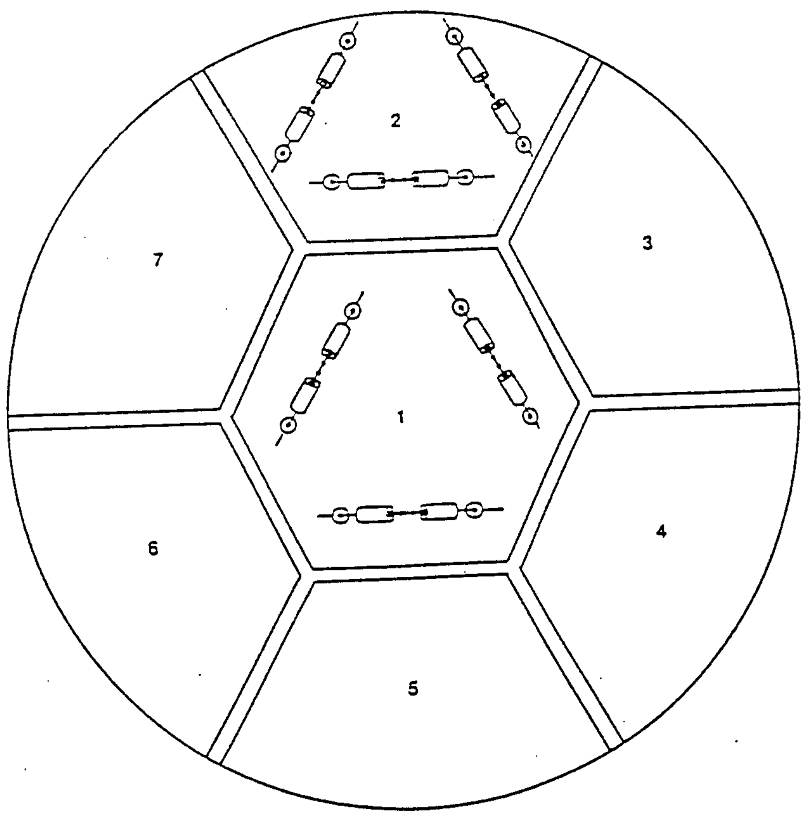


Figure 5.2.1.5 Vertical View of Bipod Actuator Location

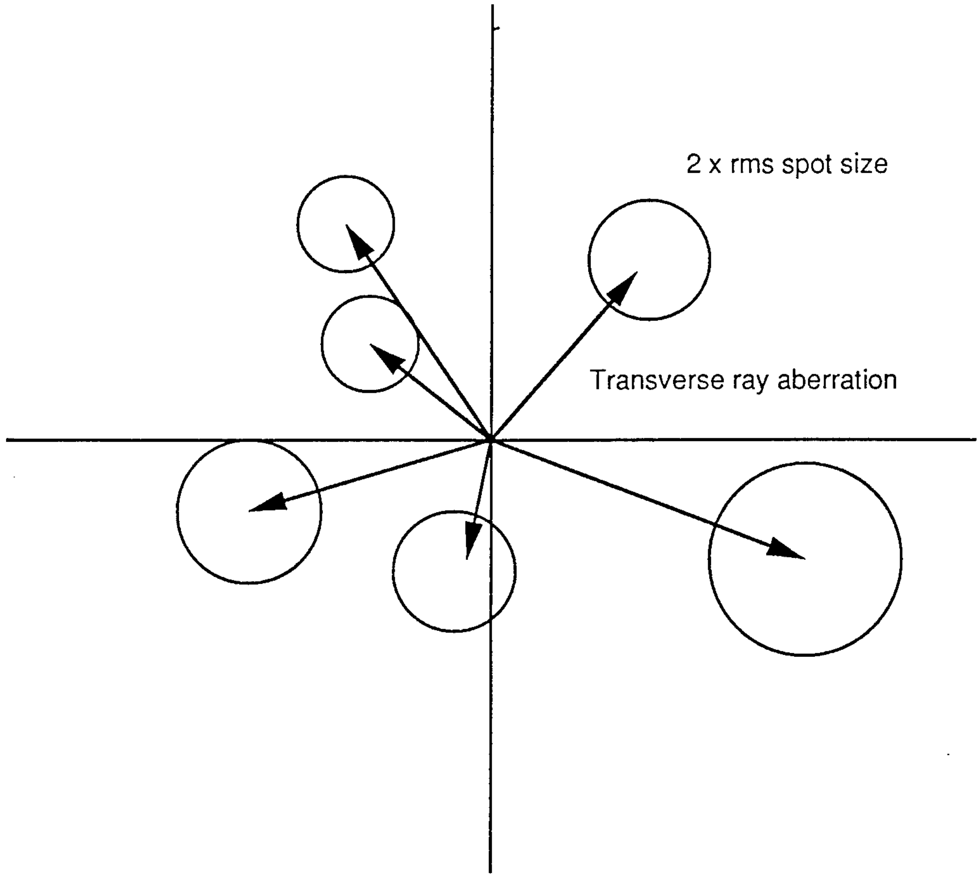


Figure 5.2.1.6 Transverse Ray Aberation and RMS Spot Size in Image Plane

5.2.1.4 Conceptual Design

Overview: The experiments will consist of:

1- Phasing of the segments of the SPICE primary mirror surrogate in the presence of scaled high power disturbances using active control as will be done in the ALI experiment,

2- Demonstration of active wavefront control of a beam expander surrogate in the presence of scaled high power disturbances, and

3- Demonstration of the Zenith Star baseline set and hold of the actuators.

Each of the petals of the SPICE primary mirror simulator will be connected to the main structure by three bipod actuator pairs. Readings of six two-axis tilt sensors, six two-axis gap sensors, and six three-axis gap sensors will be used with appropriate linear control laws to drive the petals to nominal conditions. The effect of controller bandwidth upon line of sight jitter and wavefront quality will be studied parametrically.

In preliminary assessment, it has been assumed that selection of the actuator spring frequency to be higher than important resonances of the structure will minimize changes in the dynamic characteristics of the SPICE structure caused by active control of the primary mirror surrogate. When the bipod actuators are better defined, a modal test of the SPICE structure with the active control elements in place may be required.

Structural modification: The current rigid attachments of the petals of the SPICE primary mirror surrogate to the structure will be replaced by three bipod pairs of actuators per petal. Figure 5.2.1.4 is a schematic of a bipod actuator and Figure 5.2.1.5 shows a typical arrangement of such actuators on a segmented mirror. The LAMP actuators will be considered first, with either a modified or entirely different actuator design to be used if the first choice is found to be inadequate. It is anticipated that the characterization tests required to determine the adequacy of the LAMP actuators will have been completed prior to these experiments, but, should that not be the case, such tests would be included herein. The principal disturbances associated with Zenith Star high power operation are those due to coolant flow in the cooled secondary mirror, operation of the HEL, and slewing. The first will be simulated by proof mass actuators and the others will be input via the SAVI actuators.

Control systems: Control system use will depend upon which of the objectives described above is being addressed.

1- In the demonstration of phasing of the primary mirror segments, the OSS tilt and gap measurements will be used directly. The controller will use these data to derive commands to the bipod actuators to effect a least squares fit to the correct mirror shape, that is, it will simply seek to zero the gaps and tilts. The time histories of the same set of measurements will allow calculation of the RMS residual error in the wavefront.

2- The demonstration of wavefront control is more complex in that, in addition to the gaps and tilts, the position and orientation of the secondary surrogate must be measured. The distance along the optical axis from the center segment of the primary mirror to the secondary mirror is the longest measured distance and therefore probably the noisiest measurement in the system. The input disturbances may have to be further scaled up for this effort. The controller could again try to zero all measurements, but a novel linear method that is more efficient and that more nearly simulates wavefront control in a HEL system has been defined in which the wavefront aberration may be expressed as the sum of the aberrations from each of the beam expander elements. The mathematical analysis of the method is contained in Reference 2. These calculated individual aberrations can be visualized as spots that are enlarged by piston errors and offset from the optical axis by element tilt and decentration (see Figure 5.2.1.6). They are driven toward minimum spot size and minimum offset by the control system. SPICE wavefront

correction will thereby avoid the complexities of an outgoing wavefront sensor system by concentrating on the aberrations induced by rigid body displacements and rotations of the primary mirror segments and the secondary mirror and by using a new approach to defining the merit function that will be minimized by the controller. The time history of the merit function will permit calculation of the wavefront quality.

3- Evaluation of the set and hold method of the Zenith Star space experiment will be done by aligning the beam expander with the disturbances turned off. The bipod actuators will then be commanded to remain stationary as the disturbances are applied. The merit function described above will again be recorded to determine wavefront quality.

5.2.1.5 Determination of SPICE Adequacy

Performance of the experiments described in the preceding section will entail only the following modifications to the SPICE facility:

1- The elements currently used to fasten the petals of the SPICE primary mirror surrogate will be replaced by three pairs of bipod actuators per petal.

2- A control system that uses error signals from the optical scoring sensor and the gap sensors to command the bipod actuators will be added to the apparatus.

3- Proof mass actuators capable of simulating mirror coolant flow disturbance will be affixed to the tripod legs.

5.2.1.6 Additional Hardware/Software /Facilities

The following hardware additions to SPICE are required to perform the experiments described in this section:

1. Three pairs of bipod actuators per primary mirror surrogate segment, probably of the LAMP mirror actuator design or a derivative.
2. Controller hardware: computation boards,digital to analog and analog to digital converters.
3. Proof mass actuators for disturbance input to the beam expander

5.2.1.7 Cost Estimates

Cost estimates for experiment design and performance are shown in Table 5.2.1.1.

	Experiment Design ($K)	Experiment Performance ($K)
Labor	95	165
Materials	0	0

Table 5.2.1.1 Active Segment Control Experiments Cost Estimates

5.2.1.8 Schedule estimates

The availability of the SPICE apparatus to be modified by the addition of bipod actuators on the primary mirror segments and the availability of the actuators place restrictions on when these experiments can be performed. Thus, although the design phase may be begun at any time, at this time no estimate of the earliest start date for the performance of the experiments can be made. Therefore, the schedule estimates of Table 5.2.1.2 include one unknown.

TASK	EARLIEST START	TIME REQUIRED (WEEKS)
Experiment Design	Immediately	16.0
Experiment Performance	unknown	16.0

Table 5.2.1.2. Schedule Estimates for Active Segment Control Experiments

5.2.1.9 Benefits to Zenith Star

Successful completion of the the Zenith Star flight experiment will require a formidable number of advanced technologies to not only function, but to function well together. Meaningful risk reduction experiments must therefore be performed in an environment in which as many elements of the Zenith Star experiments as possible are simulated. Demonstration of techniques for phasing of the petals of a primary mirror surrogate similar in size to the LAMP mirror on a structure of dimensions similar to ALI and Zenith Star in the presence of high power disturbances will reduce risk both to the ground test and the flight experiment. In particular, development of a quantitative basis for beam expander control tradeoffs will provide a major step forward from the current situation. Should the Zenith Star flight experiment be later found to require active control of primary mirror segments, a data base from the SPICE test bed will be a far more relevant resource than any data base from ALI.

5.2.2 ALI PM-SM Alignment System Evaluation

5.2.2.1 Objective

This section will determine whether SPICE experiments can help to reduce risk for the ALI PM-SM alignment system concept.

5.2.2.2 Zenith Star Requirement

ALI is proposing an alignment system, the telescope alignment assembly, for controlling the PM-SM misalignment due to thermal drift and low frequency vibration. This system has sensors comprised of a number of laser sources at the alignment annulus assembly (AAA) and quad-cell detectors at the secondary mirror and primary mirror locations. These sensors measure the relative motions of the secondary mirror/OWS and the primary mirror. The secondary mirror/OWS alignment will be maintained by bipod type devices actuating the secondary mirror and OWS. Questions exist as to the necessary sensor dynamic range, and actuator bandwidth. Control structure interaction may also excite flexible modes in the secondary mirror support quadrapod. Furthermore, vibrations due to the laser device secondary coolant flow and ancillary equipment may increase necessary sensor dynamic ranges, yet disturbance levels are not currently known.

5.2.2.3 Flow-down to SPICE

To perform a useful comprehensive test of the ALI alignment concept, one would need to:

1- Simulate the ALI disturbances on SPICE.

2- Replicate the ALI telescope alignment assembly and secondary mirror control on SPICE.

3- Develop telescope alignment assembly performance diagnostics.

As an alternative to replicating ALI hardware, the ALI AAA and secondary mirror could be tested on the SPICE structure.

The most important benefit that SPICE can provide to ALI with respect to secondary mirror control is to characterize the disturbances that must be compensated by the secondary mirror motion. In this regard, Section 5.4 will present details for characterizing the significant motions caused by fluid flow. Interactions between the secondary mirror control (2 Hz) and structural modes (8-10 Hz) will probably not be significant. The remaining substantial disturbance is the seismic disturbance from the HEL transmitted

through the beam control optics bench. The approach to using the present SPICE facility with only minor hardware modifications for disturbance characterization is presented in the following sections.

It does not make sense to duplicate the AAA or secondary control system because of cost and especially schedule considerations. Testing of these components is part of ALI.

5.2.2.4 Conceptual Design

The present SPICE apparatus, with the addition of the OSS, can provide most of the equipment for characterizing secondary jitter. The seismic simulators (shakers) can be operated in a range of excitation levels to produce a parametric characterization of secondary jitter power spectral density versus excitation level. The length and stiffness of the ALI secondary support is similar to SPICE, and the mode frequencies are also comparable.

The key new hardware component required to simulate ALI is the bipod secondary mount. The ALI bipod is an active component, but for the purpose of characterizing the disturbance it is sufficient to duplicate the passive properties (such as stiffness) of the bipod. In this manner the bipod response to vibrations can be faithfully simulated.

At present, the SPICE OSS measures all degrees of freedom of the secondary except piston (focus), and the measurement of piston is under review. Thus, SPICE measurements will be suitable for simulating ALI.

5.2.2.5 Determination of SPICE Adequacy

The SPICE apparatus will readily accommodate this experiment once the secondary mirror mount is in place.

5.2.2.6 Additional Hardware/Software/Facilities

The only significant addition to the SPICE apparatus that is required for it to accommodate this experiment is a bipod secondary mirror mount.

5.2.2.7 Cost Estimates

For this discussion, it is assumed that the OSS will be in place and operating when this experiment is begun. A mount for the secondary mirror is required for some other experiments that have been proposed for SPICE (see Section 5.4.2). If a suitable one is not available at the start of this experiment, then it would have to be designed and fabricated. Without the design in hand, it is believed that fabrication cost can only be guessed at and that will not be done here. In Table 5.2.2.1, estimated costs are shown for design and performance of an experiment to evaluate the ALI PM-SM alignment system.

	Experiment Design ($K)	Experiment Performance ($K)
Labor	50	55
Materials	20	0
Subtotals	70	55
Total	**$125K**	

Table 5.2.2.1 ALI PM-SM Alignment Evaluation Cost Estimates

5.2.2.8 Schedule Estimates

Earliest start date is determined by date of completion of the OSS. The estimated calendar time to perform the experiment is given in Table 5.2.2.2.

Work Item	Calendar Weeks
Design secondary mirror mount	6
Fabricate secondary mirror mount	8
Install secondary mirror mount	1
Perform experiments	5
Reduce and assemble results	4
Total	**24**

Table 5.2.2.2 Estimated schedule for ALI PM-SM alignment system evaluation.

5.2.2.9 Benefits to Zenith Star

ALI will realize reduced risk. Effective solutions to unforeseen vibration problems in ALI will have been previously investigated. When actual disturbance data is available, sensor dynamic ranges, the necessity of active structural control, and feasibility of the proposed control system will have already been evaluated.

5.2.3 Effects of High Performance Slewing of a Zenith Star-Like Beam Expander

5.2.3.1 Objective

The objective is to demonstrate high performance slewing and pointing of a large flexible Zenith Star type beam expander structure without inducing vibrations in the structure that cause large line of sight jitter, line of sight lag, and wavefront errors. A number of methods, including optimal minimum time trajectory planning, are available for this purpose and have been demonstrated, with varying degrees of success, on simple beam and truss structures. None however, have been proven on a large structure similar to the Zenith Star or space-based laser system beam expanders. Zenith Star slew profiles to be investigated will include those with non-zero final values in position, velocity, and acceleration, as required by the Zenith Star mission profiles. The experiment will quantify and minimize the line of sight and wavefront errors induced by slewing. Interaction of the different slew techniques with the high authority controller - low authority controller (HAC-LAC) active structural control and the primary mirror segment actuators, if implemented, will be evaluated.

5.2.3.2 Zenith Star Requirement

Zenith Star objectives include a low power multi-target retargeting demonstration, integrated high power rapid retargeting, active structural control, and consideration of retargeting impact on imaging and tracking. Table 3.1.2 shows the three categories of Zenith Star objectives, the first being the "must do" highest priority, the second category having "high payoff", and the third being the lowest priority. In summary, Zenith Star must demonstrate tracking and lasing performance in the presence of non-zero acceleration and rate, and immediately following a rapid retargeting. In order to maintain line of sight and wavefront control during tracking and after retargeting slews, shaped profile torque commands will necessarily be employed.

The two methods to be considered for generating torque commands that don't disturb the structure are trajectory planning and linear quadratic gaussian optimal control techniques. Performance and stability questions for each method as applied to a space-based laser type beam director must be answered.

Other programs such as Torque Actuator Controls Optimization Scheme (TACOS) and the Advanced Space Structures Technology Research Experiment (ASTREX) have developed techniques for simpler structures that are less traceable to a space-based laser system. These techniques and others can be tested, developed, and perfected on the SPICE hardware as a risk reduction task.

5.2.3.3 Flow-down to SPICE

Figure 5.2.3.1 shows the flexible structure behavior of the Zenith Star STARSIM system performance model causing secondary mirror decenter during slewing for the Zenith Star mission designated P1. Even though the P1 mission does not have large acceleration requirements, flexible mode vibrations and a large deformation that follows the acceleration profile are evident. The higher frequency vibrations drive the jitter and wavefront control system bandwidth requirements. The larger, acceleration-induced deformations cause line of sight lag and semi-static wavefront errors and drive the jitter and wavefront dynamic range requirements. Figure 5.2.3.2 shows the line of sight excitations introduced into the SPICE beam expander structure during a four degree slew in 2.16 seconds as predicted by the current SPICE beam expander structural model which as known as SPICE2. The two torque command inputs to the

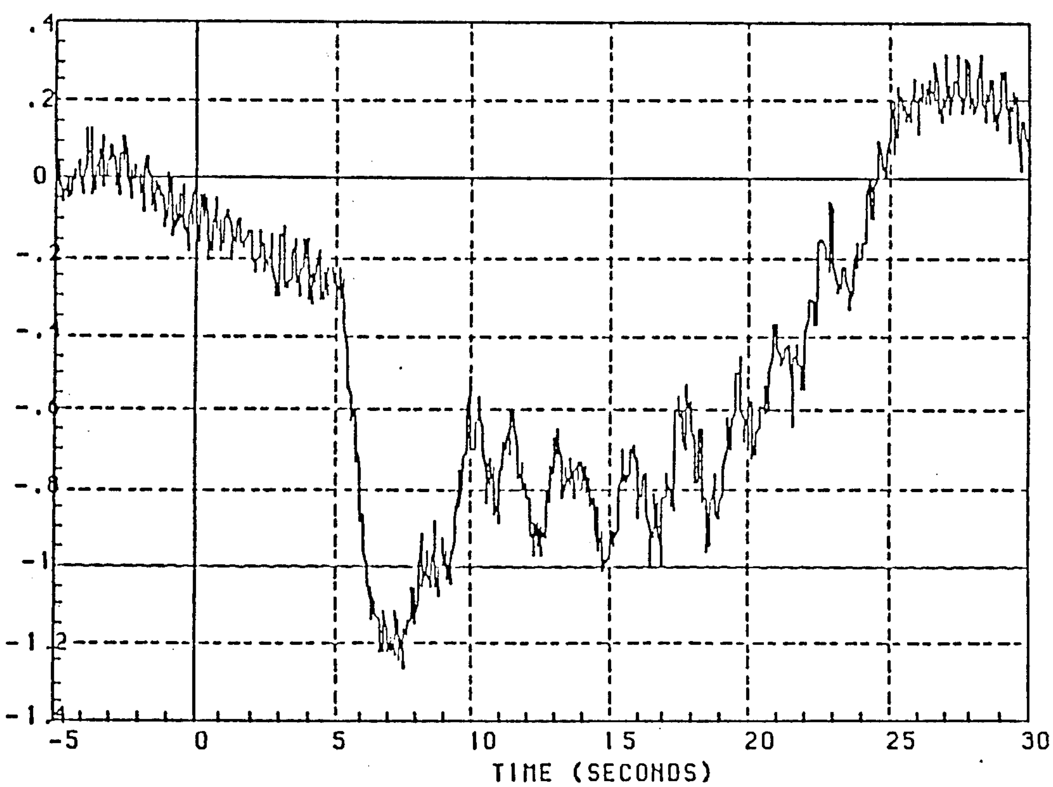
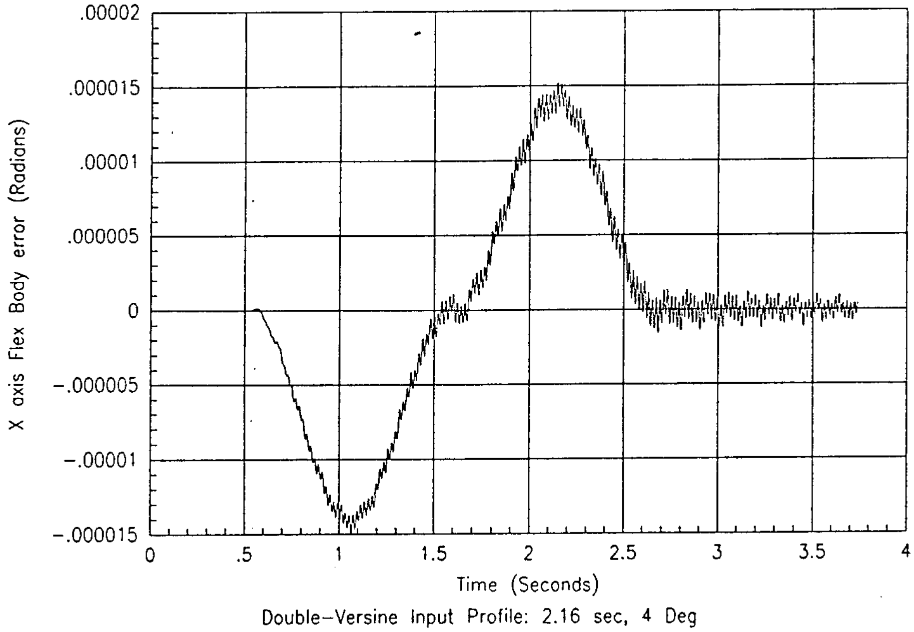
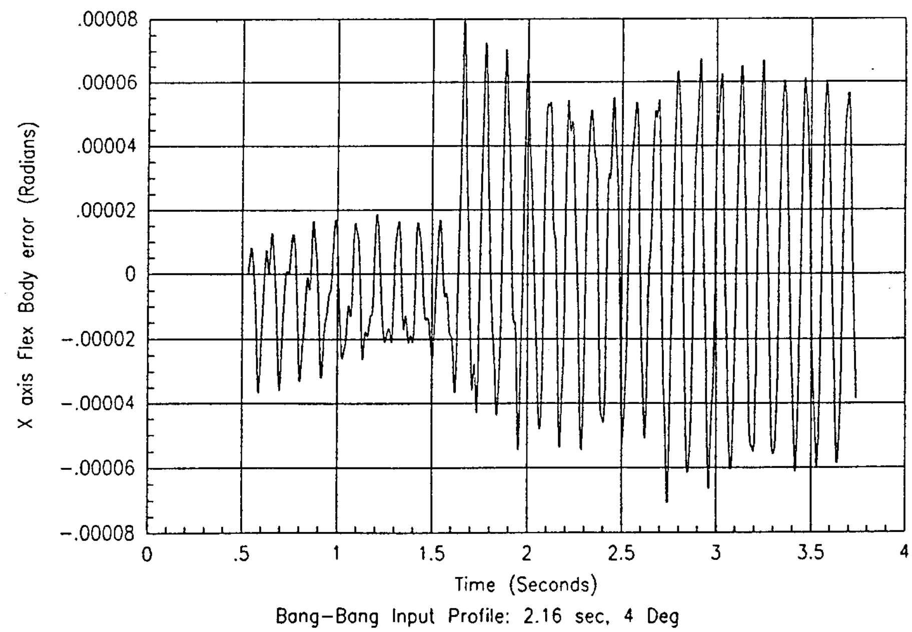


Figure 5.2.3.1 Flexible Structure Behavior of Zenith Star STARSIM Model



A. Double Versine Input



B. Bang-Bang Input

Figure 5.2.3.2 SPICE2 LOS Excitation Predictions

SPICE model are Bang-Bang and Double Versine. Similar behavior to the Zenith Star simulation is observed. This simple illustration shows that, for the SPICE2 model, the Bang-Bang technique introduces a ±65 µrad line of sight residual vibration while the Double Versine only introduces a ±1.5 µrad line of sight vibration. The disadvantage of the Double Versine is that the full 2.16 seconds are required for the four degree slew while the Bang-Bang can accomplish the slew in about half the time or 1.08 seconds. Optimal slewing techniques (Reference 3-5) can be employed to obtain time line performance similar to the Bang-Bang profile while limiting residual line of sight jitter errors to less than one µrad. A notable result of this simple simulation is that the line of sight jitter is primarily due to a limited number of modes being excited by the torque inputs. The method proposed by Breakwell in Reference 3 is especially attractive since it allows for slewing while specifying an arbitrary number of modes not to be excited. Additionally, the above techniques could be used to evaluate performance for the actual Zenith Star mission profiles which have non-zero final acceleration, rate, and position slews. Optimal slewing techniques can also be combined with the active structural control to minimize the line of sight jitter and with the active primary mirror segment control to minimize the line of sight lag and wavefront errors

5.2.3.4 Conceptual Design

Overview: The SPICE apparatus, as it will exist after the precision pointing task with the OSS would be used for this experiment. Methods for slewing the beam expander would be modeled with the SPICE3 beam expander structural model that is now under development, or the best available model. Once proven in the models, the slewing commands will be implemented with the SAVI actuators while the rigid body and flexible body deformations are measured by the SAVI and OSS respectively. The dynamic range and noise floor of the OSS will be different from the precision pointing task due to the noisier environment during slewing, but it is assumed that the OSS will be adequate. A second issue to be investigated is the interaction of the HAC-LAC active structural controller with the slewing. To determine this interaction, slew commands will be input to the simulation with the HAC-LAC system running, and after optimization, to the SAVI actuators to determine performance.

Experiment Design: Phase One of the experiment will develop a set of shaped torque and optimal slew commands to be tested. Figure 5.2.3.3 shows some candidate shaped torque profiles that have been investigated on simpler structures. The Figure shows the jerk, acceleration, rate and position profiles for each technique. The proposed linear quadratic gaussian method considers two possibilities: open and closed loop slewing. The open loop method calculates the optimal trajectory based on quadratic cost functions that include a subset of the structure's modal dynamics and control effort. The closed loop method utilizes feedback to improve on the open loop method.

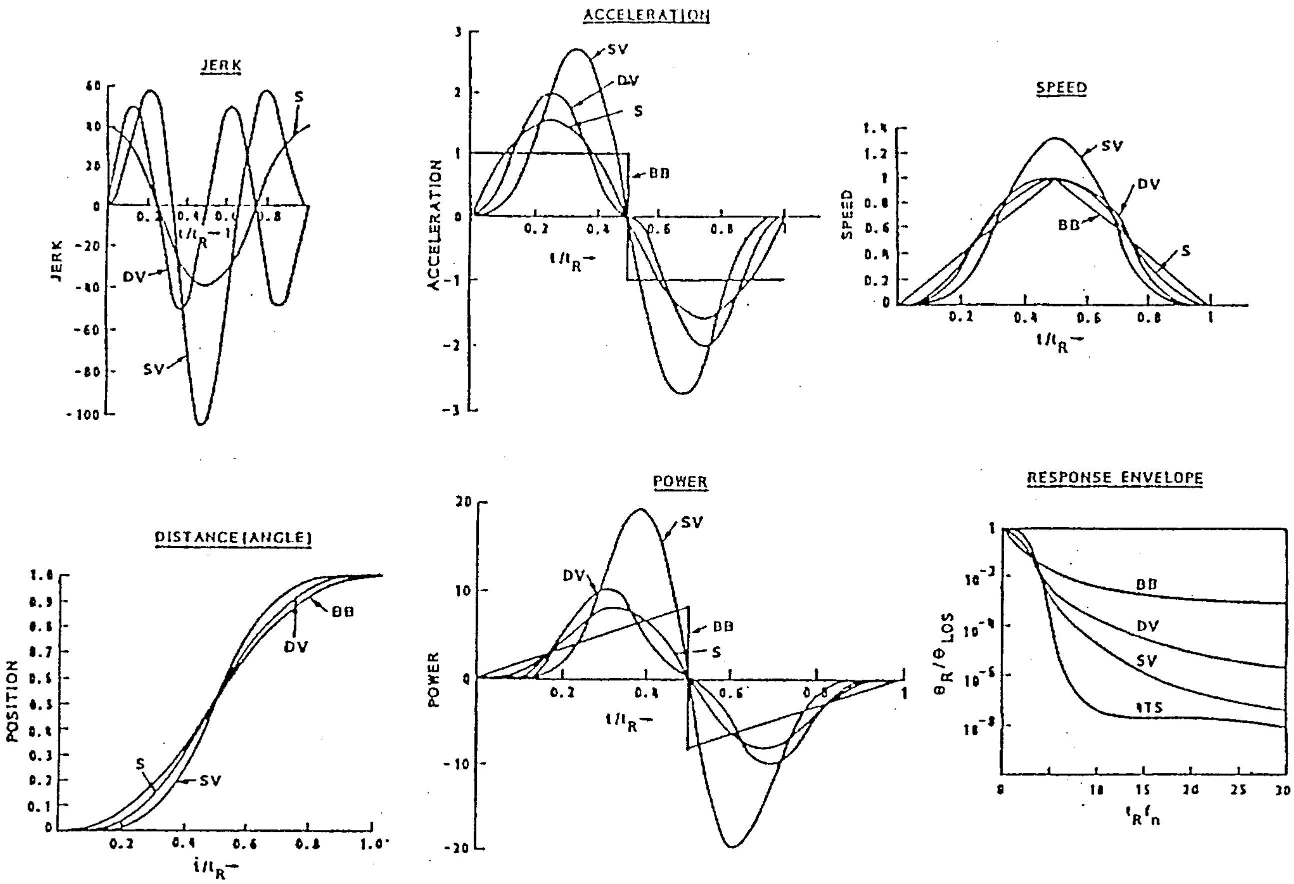


Figure 5.2.3.3 Properties of Various Forcing Functions

Phase Two of the experiment involves implementation of the proposed slewing techniques on the SPICE hardware as well as data acquisition, reduction and performance evaluation. Since all of the necessary equipment will be in place at the end of the precision pointing experiment, only a test plan will have to be developed.

5.2.3.5 Determination of SPICE Adequacy

Since the SPICE hardware is highly representative of the Zenith Star system, the results obtained from this experiment would be usable directly in the design of the Zenith Star pointing system. The current SAVI system has maximum jerk, force, rate, and position limits (see limits in Table 5.1.3.1). These limits are quite large, but not all Zenith Star missions could be simulated with SPICE due to one limit or another. None the less, most Zenith Star issues can be resolved, and high performance slewing methods can be developed and proven with the SPICE hardware.

5.2.3.6 Additional Hardware/Software/Facilities

No additional hardware above and beyond what will exist for the precision pointing experiment is required for this task since slewing techniques can be evaluated without a target dynamics simulator or a tracking system.

5.2.3.7 Cost Estimates

In Table 5.2.3.1, estimated costs are shown for design and performance of the high-performance slewing experiment.

	Experiment Design ($K)	Experiment Performance ($K)
Labor	75	70
Materials	0	0
Subtotals	75	70
Total	$145K	

Table 5.2.3.1 High-performance Slewing Experiment Cost Estimates.

5.2.3.8 Schedule Estimates

In Table 5.2.3.1, estimated schedule is shown for design and performance of the high-performance slewing experiment.

Work Item	Calendar months
Develop techniques and simulations, test plans etc.	2
Perform experiment, take data, and repeat as necessary	1

Table 5.2.3.1 High-performance Slewing Experiment Schedule Estimates.

5.2.3.9 Benefits to Zenith Star

The evaluation of high-performance slewing effects upon a large flexible beam expander structure will provide a data base for the design of slew command profiles. Zenith Star will benefit from performance evaluation of techniques developed on other programs and applied to Zenith Star type structures. This will reduce risk for the Zenith Star experiment and provide technology transfer from other programs, thereby increasing the overall probability of success.

5.2.4 Separate Aperture Tracker Effects/Performance

5.2.4.1 Objectives

The objective of this experiment is to evaluate aspects of the Zenith Star boresighting method and to examine structural effects of the tracker mass.

5.2.4.2 Zenith Star Requirement

The Zenith Star concept is based on a separate tracker telescope located on one of the primary segments which is obscured from the HEL. During track, and especially during HEL pointing, it is important that the tracker and the HEL beam director be aligned (boresighted). The Zenith Star alignment concept is to employ an 8 cm diameter alignment reference beam to link the tracker and HEL beam director in such a manner that pointing performance is immune from relative motion of the tracker and beam director.

Figure 5.2.4.1 shows the alignment reference laser mounted on a stable platform between the tracker and the center of the HEL output aperture. The laser beam is split and directed via an extended corner cube to the tracker and beam director. So long as the output beams of the extended corner cube are parallel, the tracker and HEL can be aligned.

There are three potential Zenith Star issues related to the separate aperture tracker concept. The first two directly concern the tracker/HEL alignment, whereas the third issue is related to the general problem of attenuating mechanical/structural disturbances. These issues are:

1- Extended corner cube performance: How well can the output beams of the extended corner cube be kept parallel?

2- Reference beam measurement error: How well does the tilt on the 8 cm reference beam measure the tilt over the full 4 meter HEL beam director aperture?

3- Tracker mass: How does the additional mass of the tracker (> 1000 lbs) affect the structural response?

The following sections will consider the importance of these three issues and how SPICE might assist in risk reduction.

5.2.4.3 Flow-down to SPICE

The first potential issue, maintaining parallel beams at the output of the extended corner cube, depends on minimizing stress in the structure holding the extended corner cube optical elements. There are several reasons why using SPICE to test the performance of an extended corner cube would probably not be a useful application of SPICE resources.

The Zenith Star extended corner cube and stable platform is not a long lead item, and it can be designed and tested independently of other critical assemblies such as the tracker and beam director. Thus, development within the Zenith Star program poses very little cost/schedule risk.

Prior experience, including the fabrication of an articulated reference transfer system (ARTS) for the bifocal program at the Weapons Laboratory, has demonstrated performance exceeding Zenith Star requirements. Therefore, the extended corner cube poses only limited performance risk.

The second issue, namely the ability of the 20 cm reference beam to sense the tilt over the full aperture, is much more substantial, and is directly related to the SPICE program. First, the reference beam "sees" only one segment of the primary, so any tilt of the other segments relative to the reference segments is unsensed. Since the system is aligned on orbit prior to firing the HEL, the errors of concern are only dynamic errors. Next, the reference beam "sees" only a small portion of the primary reference segment and also only a small portion of other optical elements in its path. Thus, a localized dynamic wavefront distortion in the path sensed by the alignment reference beam can cause an erroneous tilt observation. This portion of the problem concerns bending or thermal distortion of the optics and therefore is not directly an issue which SPICE can address without adding a real primary segment.

The OSS is currently designed to measure primary mirror segment tilts relative to the central petal (see Figure 5.2.4.2). This is just what is required to address the above issue of the ability of the Zenith Star alignment beam to sense only the central segment of the primary mirror. Moreover, the short enclosed atmospheric path within the SPICE OSS enables submicroradian segment tilt measurement which is adequate to scale to Zenith Star requirements. The sole requirement for SPICE is to develop an alignment performance metric for the difference in full aperture and single segment tilt and to implement data processing software to calculate alignment performance.

The third separate aperture tracker issue concerns the additional weight and movement of the Zenith Star capture tracker. Figure 5.2.4.3 shows the size of the capture/track telescope assembly and Table 5.2.4.1 shows that the capture/track subsystem has substantial mass relative to the entire beam expander

subsystem. A Lockheed Engineering Analysis Language (EAL) structural analysis was performed on the Zenith Star forward body, and a summary of results is shown in Table 5.2.4.2. The capture/track subsystem is involved in a substantial number (79) of the system modes below 200 Hz. Moreover, the capture/track subsystem is involved in nearly twice as many modes as the primary segments. Thus to make SPICE traceable to Zenith Star, a realistic upgrade would be to add a capture/track mass simulator to one of the primary segments or to the truss directly. In this manner the structural characteristics of SPICE would simulate the real Zenith Star system.

Beam Expander Subsystem Mass Properties		**Capture/Track Subsystem Mass Properties**	
X-CG	5.8 in	X-CG	-12.1 in
Y-CG	4.6 in	Y-CG	-49.2 in
Z-CG	-2.6 in	Z-CG	29.9 in
MASS	23.2 snails	MASS	12.1 snails
IX-X	8.4×10^4 snail-in^2	IX-X	1.0×10^4 snail-in^2
IY-Y	14.5×10^4 snail-in^2	IY-Y	1.1×10^4 snail-in^2
IZ-Z	13.9×10^4 snail-in^2	IZ-Z	1.0×10^4 snail-in^2

1 snail = 1 lbf-s^2/in. CG = center of gravity. I = moment of inertia

Table 5.2.4.1 Mass properties of Zenith Star beam expander and capture/track subsystems.

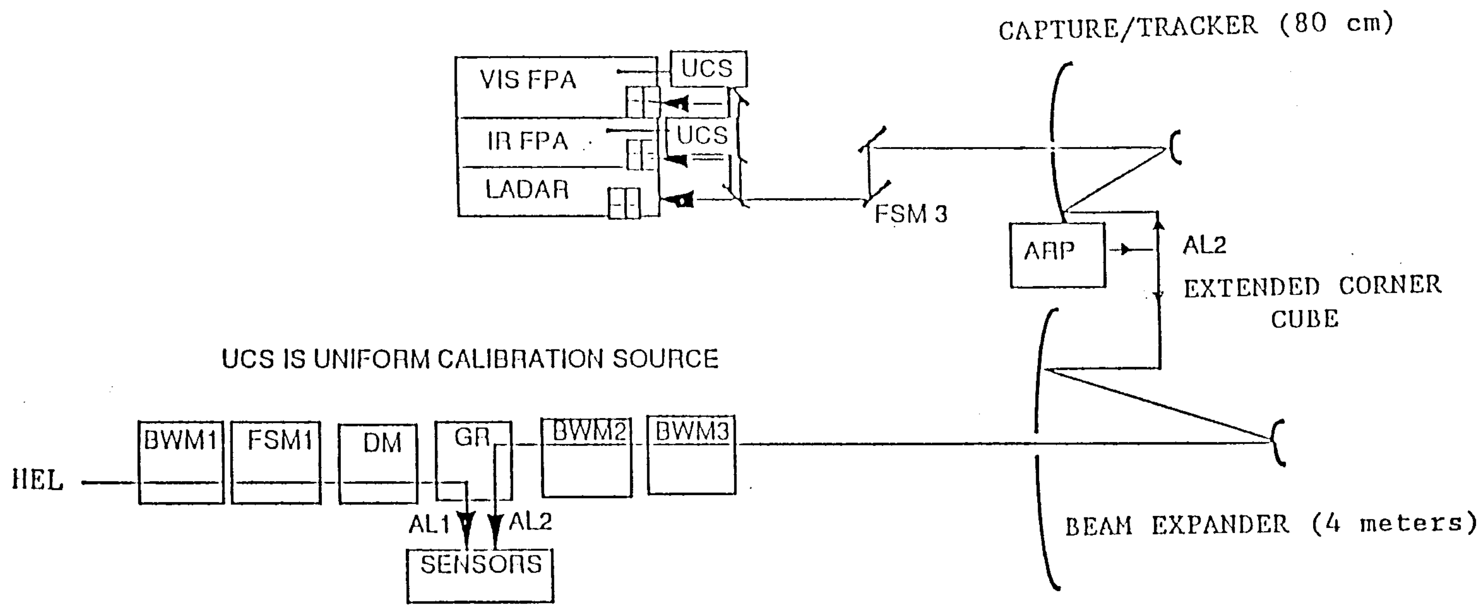
5.2.4.4 Conceptual Design

Figure 5.2.4.4 shows the software needed to produce a boresight alignment metric. Although segment tilts will be the largest factors involved in boresight alignment, there is also an error due to piston of the primary segments. Thus, both tilt and piston error, which are measured from the gap senors and the OSS, are inputs to a simple diffraction propagation model to estimate the far field centroids of the reference and full aperture target beams. The difference of these two centroids provides the boresight error metric. Far field propagation can probably be accomplished with a simplified model since the wavefront errors here are just linear functions.

SUB-COMPONENT	No. of Active Degrees of Freedom	Highest Node Number	Model Weight (lbs)	Constrained Funda-mental Freq.	No. of Modes Below 200 Hz	No. Boundary Nodes
Beam Expander subsystem	2640	463	8941	16.4 Hz	32	107
Capture/Track subsystem	3000	1038	4681	1.4 Hz	79	34
Shroud (doors open)	1398	575	795	3.0 Hz	134	37
Shroud (doors closed)	1398	575	795	12.9 Hz	123	37
Primary Mirror Center	2340	3066	800	30.6 Hz	37	6
Primary Mirror Edge	1170	3041	562	30.9 Hz	39	6
Beam Control Transfer Subsystem	1254	329	6852	10.0 Hz	28	8

Table 5.2.4.2 Phase IIIA model summary.

The addition of the capture/track mass simulator is shown in Figure 5.2.4.5. Currently SPICE weight is estimated to be within 500 lbs. of the load limit of the roof of the building, so the key issues are to determine exactly the weight/moment limits of the present structure, and then to determine whether SPICE experiment results with allowable mass/moments would be scalable to Zenith Star. There are plans to replace the current SPICE gravity offload with a pneumatic/electric gravity offload to support future SPICE experiments.



An alignment laser beam (AL1) on the Zenith Star alignment reference platform (ARP) enables the HEL spot to be placed on target using only the separate aperture tracker for pointing information.

Figure 5.2.4.1 Tracking Method

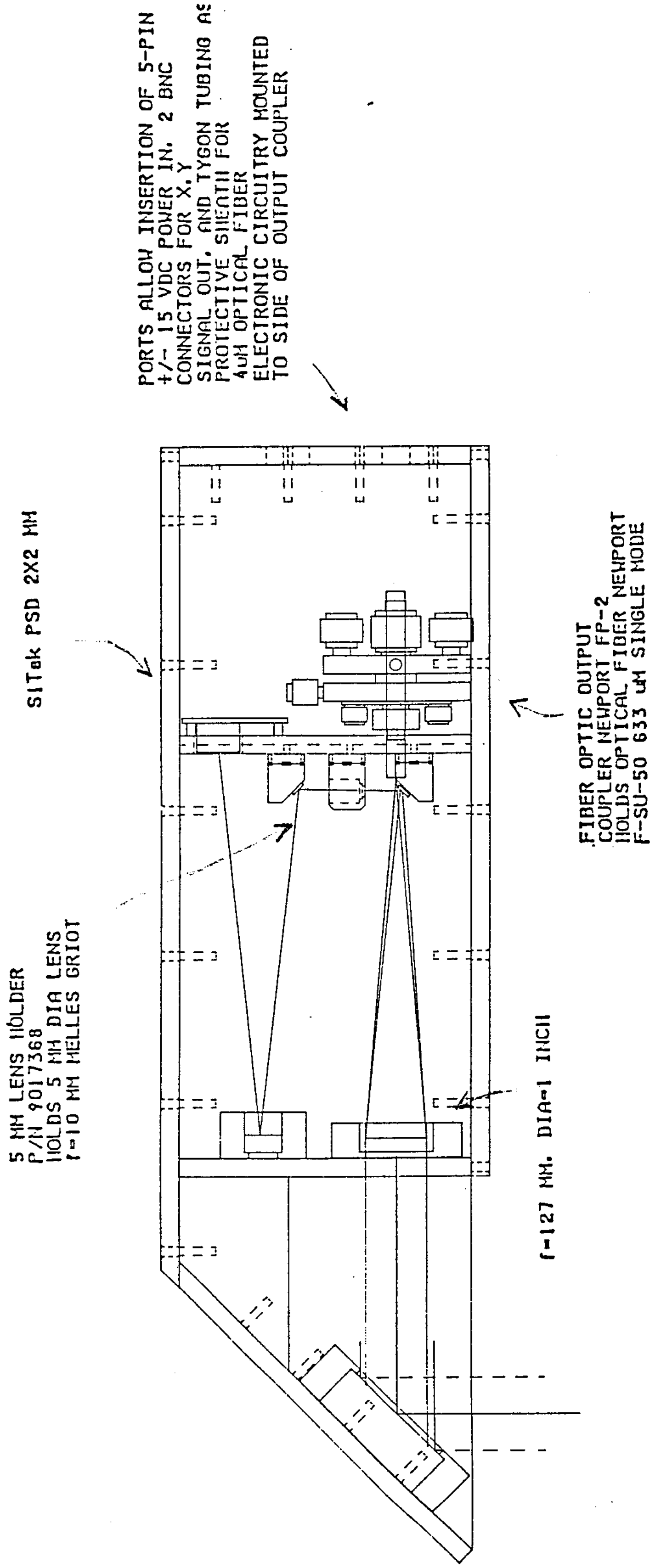
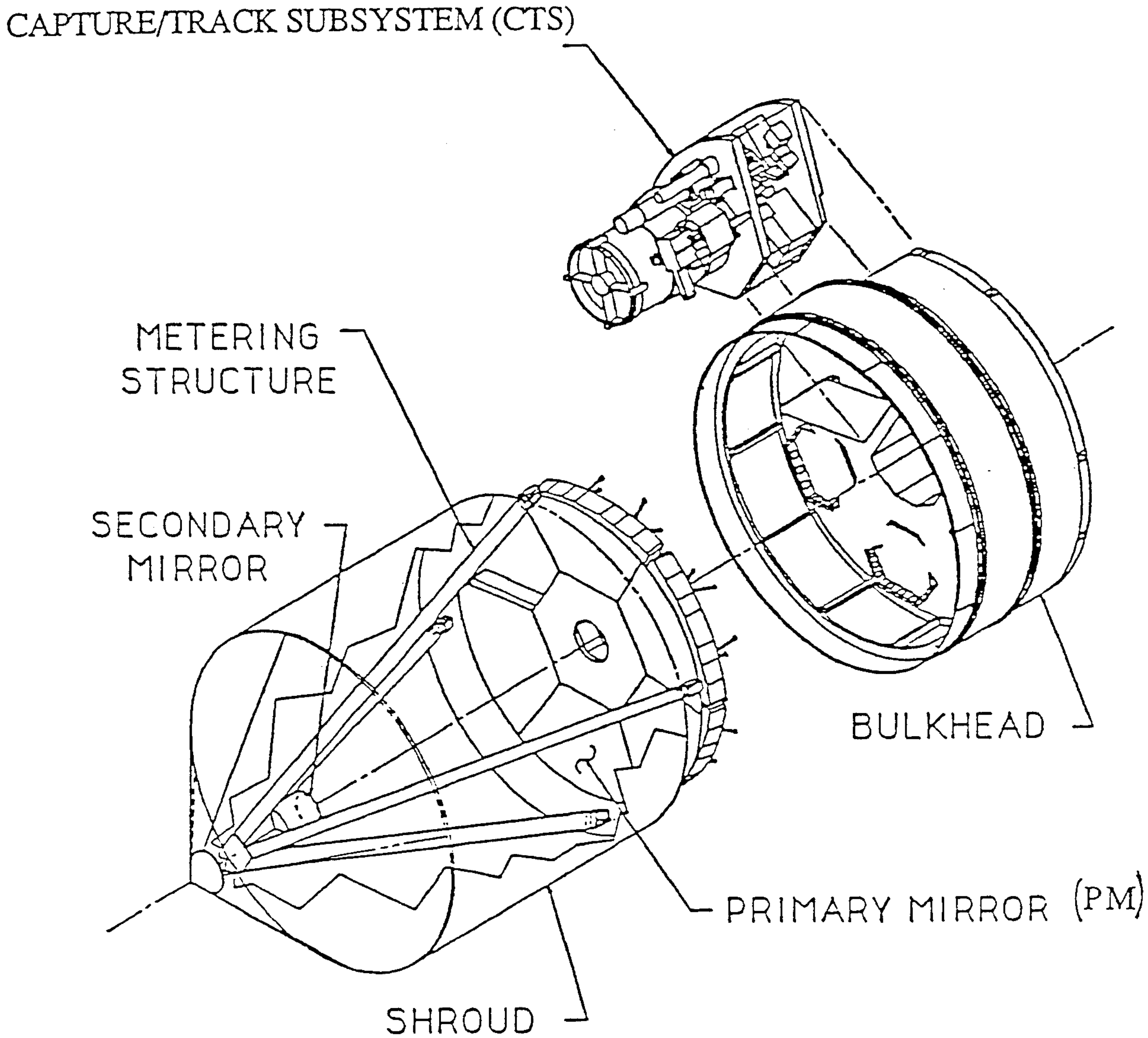


Figure 5.2.4.2 Petal Tilt Sensor



The Zenith Star forward body, showing how the capture/track subsystem is mounted in place of one of the primary segments.

Figure 5.2.4.3 Relative Size of Capture/Track Subsystem

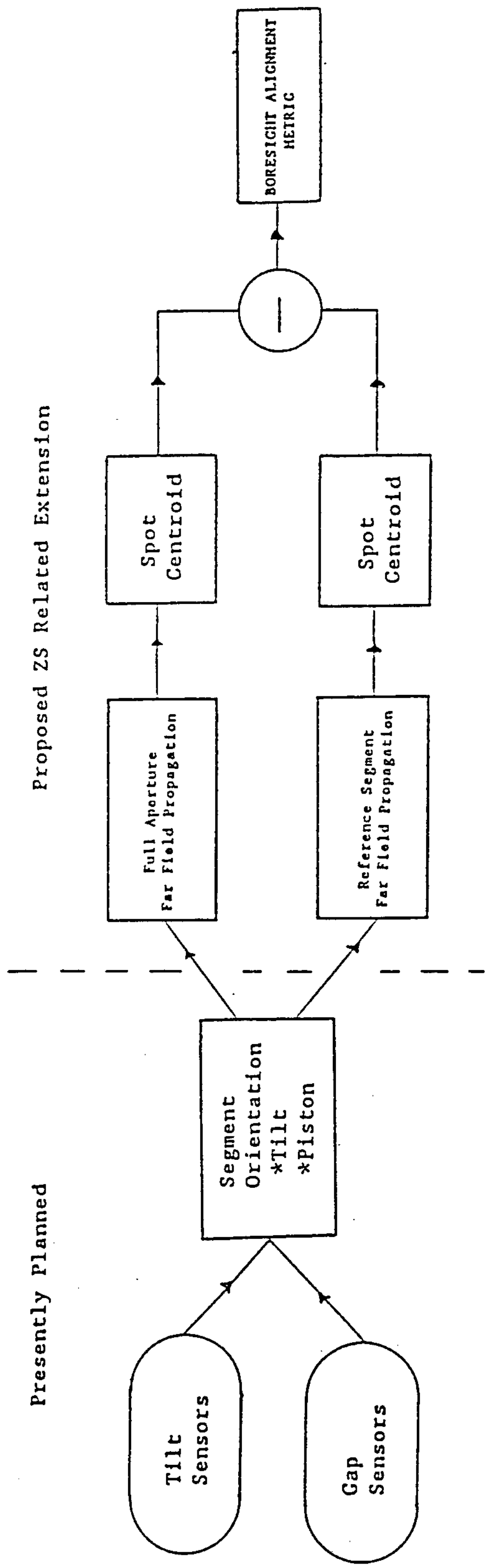


Figure 5.2.4.4 Boresight Alignment Metric Software

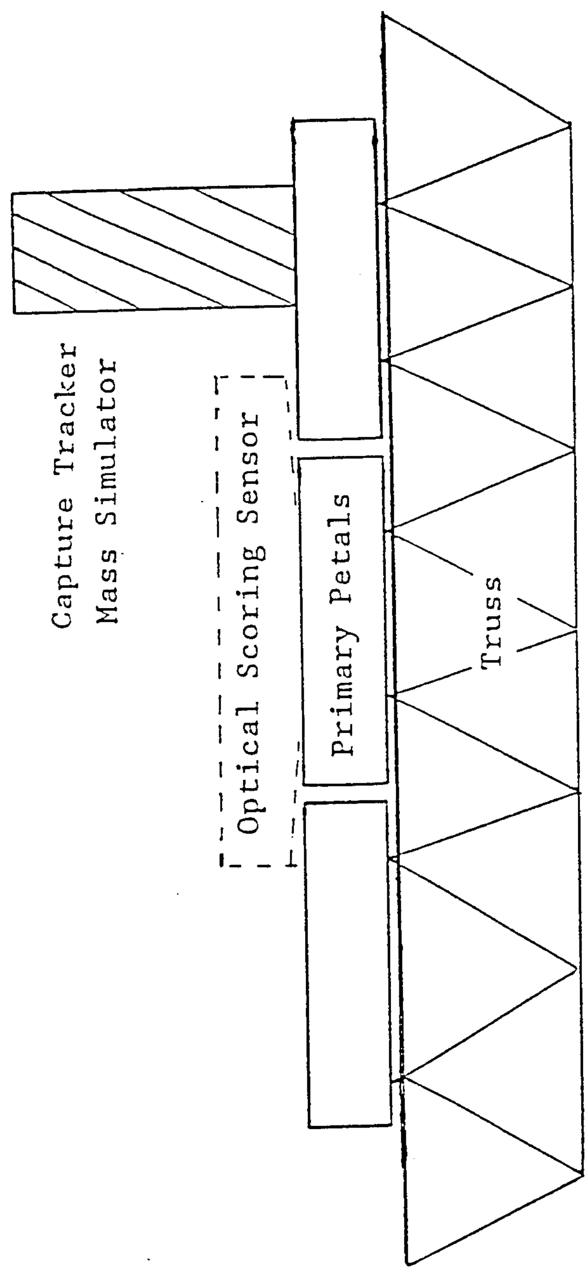
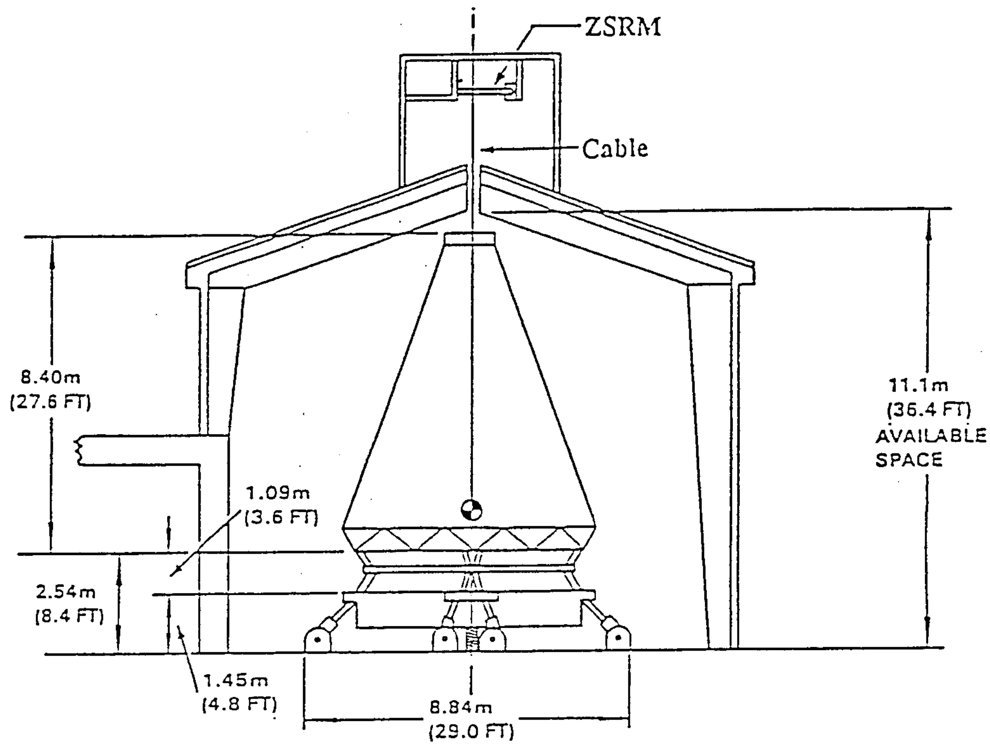
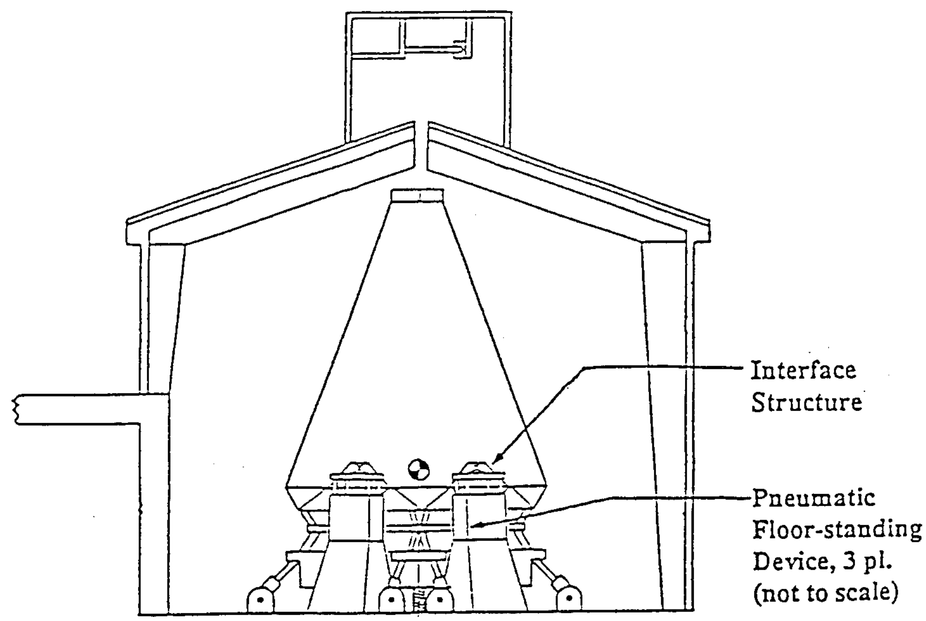


Figure 5.2.4.5 Zenith Star Capture Mass Simulator





SPICE gravity offload concepts. Top figure is the present zero spring-rate mechanism (ZSRM) system and the bottom figure is the pneumatic support concept.

Figure 5.2.4.6 SPICE Gravity Offload

5.2.4.5 Determination of SPICE Adequacy

SPICE hardware currently being fabricated is suited to the introduction of a tracker/HEL boresight alignment metric as described above. The HP9000 computer for high speed data collection and the VAX (or Cray) for post-processing provide computational capability to implement the boresight alignment metric.

Addition of a tracker mass simulator poses a critical SPICE adequacy issue. The addition of the tracker to Zenith Star moves the center of gravity approximately 1.5 feet off axis. The SPICE gravity offload (Figure 5.2.4.6) requires a symmetric mass distribution to limit the load on the magnetic isolators. The attachment point on the primary center petal may be moved laterally by a few inches without major impact, to accommodate a displacement of the center of gravity. This flexibility is inadequate for the offset of the center of gravity corresponding to a tracker mass similar to that of Zenith Star.

There are three alternatives for the gravity offload to accommodate the tracker mass simulator. The first two involve modifying the present offload system, whereas the third requires replacement of the present system by a pneumatic suspension. The alternatives are:

1. Move the gravity offload ceiling attachment to a point directly above the new center of gravity with tracker mass simulator added.
2. Move the SAVI structure laterally by the same amount.
3. Replace the present gravity offload system with the pneumatic offload being developed by CSA Engineering (Reference 6).

All of the above alternatives are relatively costly and complicated. The most efficient manner of achieving the objective is to try to accommodate the new center of gravity in the course of changes to SPICE that are already being contemplated. For example, the gravity offload and/or the SAVI position may be moved to install the isolation chamber. If the center of gravity displacement was considered simultaneously, then a cost effective solution might be found. Also, if the pneumatic suspension was adopted for other reasons, then the objective would be achieved at zero cost.

5.2.4.6 Additional Hardware/Software/Facilities

Hardware: A tracker mass simulator must to be added to the SAVI/SPICE structure in place of one of the segments of the primary mirror surrogate.

Software: Development and implementation of an alignment performance metric are required.

5.2.4.7 Cost Estimates

Table 5.2.4.3 assumes that the OSS will be in place and operating when this experiment is begun. The design of the separate aperture tracker mass is included here but, without the design in hand, the fabrication cost can only be guessed at and that will not be done here. It is assumed that the pneumatic/electric gravity offload will be in place if needed. If not, then an additional $300K would be required if the mass of a reasonable simulator of the Zenith Star tracker cannot be supported by the current offload device. Estimated labor hours are shown separately for design and installation of a tracker surrogate.

Table 5.2.4.3 shows the estimated costs for design and performance of the separate aperture tracker effects experiment.

	Experiment Design ($K)	Experiment Performance ($K)
Labor	90	70
Materials	20	0
Subtotals	110	70
Total	**$180K**	

Table 5.2.4.3 Separate Aperture Tracker Effects Experiment Cost Estimates.

5.2.4.8 Schedule Estimates

Earliest start date is determined by date of completion of OSS, and/or of the required gravity offload. Table 5.2.4.4 is the calendar time estimate for this experiment.

Work Item	Calendar Weeks
Design work	10
Fabricate secondary mirror mount	7
Installation of tracker mass, software	3
Perform experiments	5
Reduce and assemble results	4
Total	**29**

Table 5.2.4.4 Estimated calendar time for separate aperture tracker effects experiment.

5.2.5 Use of Smart Struts to Improve Line of Sight, Wavefront Stability

5.2.5.1 Objectives

The objective of this experiment is to demonstrate the utility of active structural members in improving line of sight and wavefront quality in a HEL system test bed.

5.2.5.2 Zenith Star Requirements

In a space-based HEL system, a major source of beam degradation is structural vibration. Zenith Star has several goals that require a high on-axis intensity in the focal plane which is equivalent to requiring that the beam leaving the Zenith Star beam expander be of high quality, i.e., of low phase variance. Zenith Star will be conducted in an environment free from atmospheric beam degradation but fairly rich in mechanical disturbances that distort the beam expander and thereby induce distortions into the HEL phase. Experience has shown that the simple requirement that a good quality HEL beam leave the beam expander leads to a need to employ a variety of techniques to fight disturbances. The speed with which retargeting can be accomplished will be affected by the beam jitter introduced by slewing to effect retargeting. Use of smart struts, i.e. structural elements with internal active control, is one of the techniques that, alone or in conjunction with other vibrational suppression methods, may provide important mechanical disturbance suppression. Therefore, the use of smart struts could potentially be a major contributor to the Zenith Star system meeting its target engagement and rapid retargeting requirements.

5.2.5.3 Flow-down to SPICE

The SPICE beam expander tripod and the Zenith Star beam expander quadrapod are similar structures. The SPICE tripod struts are about 8.5 m in length and 17 cm in diameter, which may be compared to the rectangular Zenith Star and ALI quadrapod struts which are 6.0 m in length and, respectively, 10 cm X 22.5 cm and 12.5 cm X 22.5 cm. The SPICE primary mirror simulator is 5.6 m in diameter and the LAMP diameter is 4.0 m. The SPICE beam expander therefore has about the same shape as the Zenith Star beam expander and is about forty percent larger. Demonstration of line of sight and wavefront disturbance suppression on SPICE would be traceable to Zenith Star without difficulty.

5.2.5.4 Conceptual Design:

The strong analogy between the SPICE and Zenith Star beam expanders is not the only reason to consider use of smart struts for the metering structure. Table 5.2.5.1 shows the relative weighted strain energy storage at various sites in the SPICE structure. The weighting is such that the numbers in the table tell the relative effect upon the line of sight jitter of vibration at each site. Suppression of vibration in the tripod struts has by far the largest potential for line of sight jitter suppression. A similar analysis of the Zenith Star structure has not been performed, but it is conjectured here with some confidence that at least qualitatively similar results will be obtained.

	4th-Order Rolloff	Flat Spectrum
BULKHEAD STRUCTURE	11.46%	17.00%
TRIPOD LEGS	62.93%	58.78%
TOP HORIZONTAL BEAMS	0.42%	0.39%
TOP DIAGONAL BEAMS	4.33%	3.90%
HORIZONTAL BEAMS FROM TOP CLAMPS	1.04%	0.97%
BEAMS TO TRIPOD LOWER CLAMPS	3.43%	3.19%
BEAMS TO VERTEX OUTER NODES	14.86%	14.01%
MAGNETIC ACTUATOR OUTER PLATES	0.19%	0.18%
SECONDARY MIRROR	0.69%	0.63%
PRIMARY MIRROR PETALS	0.62%	0.91%
BARS FROM CENTER PETAL TO BULKHEAD	0.03%	0.05%
ALL ELEMENTS	**100.00%**	**100.00%**

Table 5.2.5.1 Relative stored strain energy in SPICE apparatus under excitation.

A typical smart strut design is shown in Figure 5.2.5.1. Strips of piezoelectric material are embedded in the walls of a hollow strut. Active control of the electric fields across the strips permits countering of compression/extension distortion as well as bending in two orthogonal axes. The experimental procedure envisioned is:

1- Select a disturbance set that has been already used with the regular tripod so that comparison results will be available.

2- Replace a tripod leg with a smart strut of the same length (8.5 m).

3- Replicate the earlier experiments with the smart strut in place. Use other loops open, then closed.

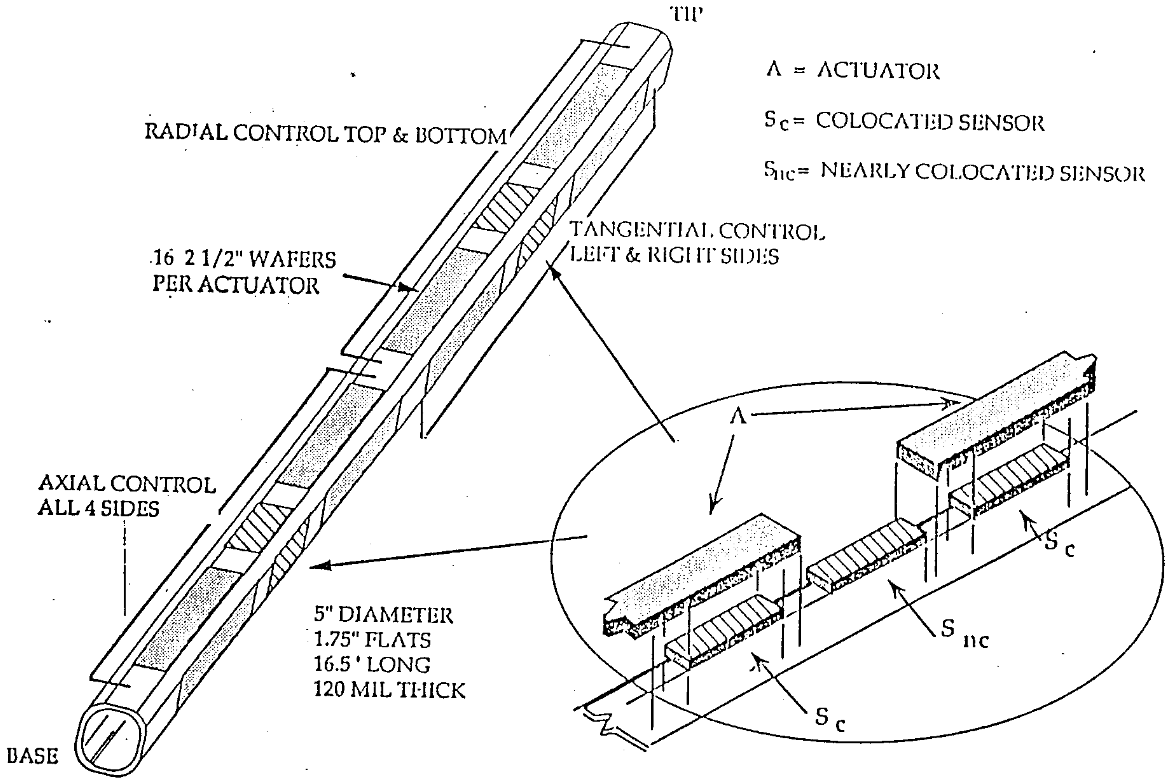


Figure 5.2.5.1 Active Tripod Leg Control Schematic

5.2.5.5 Determination of SPICE Adequacy:

The SPICE structure requires no modification other than the actual tripod strut replacement by a smart strut. It is the most qualified test bed for the experiment. Unlike, the ASTREX structure, SPICE has an OSS which allows direct observation of jitter and low-order wavefront distortion. The question of interest to Zenith Star does not concern suppression of structural vibration but rather suppression of beam HEL jitter and wavefront distortion.

5.2.5.6 Additional Hardware/Software/Facilities

One or more smart strut replacements for tripod struts is required.

5.2.5.7 Cost Estimates

Table 5.2.5.2.shows the estimated costs for design and performance of the SPICE smart strut experiment.

	Experiment Design ($K)	Experiment Performance ($K)
Labor	85	80
Materials	Smart Strut Fabrication	0
Subtotals	85 plus Fabrication	80
Total	**$165K plus Smart Strut Fabrication**	

Table 5.2.5.2 Smart Strut Experiment Cost Estimates.

5.2.5.8 Schedule estimates

Schedule estimates for the experiment design and experiment performance phases are shown in Table 5.2.5.3.

Work Item	Calendar Weeks
Design efforts	5
Remove tripod leg	1
Install smart strut tripod leg. and check out structure	2
Perform line of sight, wavefront quality measurements	3
Reduce and assemble results	4
TOTAL (exclusive of fabrication)	**15**

Table 5.2.5.3 Estimated calendar weeks for SPICE smart strut experiment.

5.2.5.9 Benefits to Zenith Star

The smart strut is one of several disturbance suppression techniques of which some or all will be required for a Zenith Star or a space-based laser to produce an intense beam at the desired point in a distant focal plane. Tradeoffs involving the candidate technologies will be accomplished in a reasonable way only if

knowledge of benefit, complexity, and cost are available. The experiment proposed will answer key questions about benefit to the beam quality of the use of smart struts.in a complex environment. The smart struts will have to perform on the SPICE structure with other control loops operating. Cost data concerning smart strut operation and maintenance will become available from this and other experiments that use them.

5.3 Advanced Materials and Passive Damping Experiments

Conceptual designs of three experiments in the areas of advanced materials and passive damping applications to improved Zenith Star line of sight and wavefront quality are presented in this section:

- Advanced composite materials experiments: Use of the very stiff composite materials such as Graphic/Epoxy-fiber/matrix (Gr/Ep) to improve Zenith Star performance.
- Passive damping of tripod (or quadrapod) modes of a beam expander: Passive damping of low order modes of the large struts that support a beam expander.
- Passive damping of modes of a segmented mirror: Passive damping of modes of the primary mirror and its backup structure.

5.3.1 Advanced Composite Materials

5.3.1.1 Objectives

The Advanced Composite Materials Task is in support of the Zenith Star Space Experiment.

Satellite programs normally attempt to solve precision requirements with conventional materials and it is only when the requirements cannot be met and there is no relief from the requirements that a program will consider new materials. One of the objectives of this task is to remove that barrier to this resistance by demonstrating emerging technologies on the SPICE testbed. When inserting new materials in a satellite program there are several issues that need to be addressed including producibility, repeatability, reliability, flight qualifiability, space qualifiability, and performance requirements. The Advanced Composite Materials Task addresses all of these issues.

While significant advantages of using advanced composites have been established at the component level, only limited fabrication and testing have been conducted at the full-scale structure level. Therefore, this task offers a timely and unique opportunity to establish system application confidence in advanced materials and structures technologies by designing and fabricating a full-scale space structure from near state-of-the-art composites [e.g., graphite/magnesium (Gr/Mg), graphite/aluminum (Gr/Al), and discontinuous silicon carbide/aluminum (SiC_d/Al)] and subsequently conducting dynamic testing using the SPICE testbed to verify enhancements in structural performance.

5.3.1.2 Zenith Star Requirements

The objective of the Zenith Star Experiment is to define and demonstrate space-based laser technology. The Zenith Star Experiment, is a single free-flying spacecraft measuring approximately 84 ft. long, 15 ft. in diameter, and weighing nearly 100,000 lbs. The spacecraft is separated into a forward body and an aft body. The forward body contains the beam expander, the beam control optics, and the acquisition and tracking sensors, while the aft body contains the laser device and propellants. The primary mission will be to track and use ground-launched test objects, celestial test objects, ground test objects, and on-board test objects. At the conclusion of the primary mission, the aft body will be dropped and the forward body will be boosted to a higher orbit to perform the science mission. During the science mission, the remainder of the spacecraft will function as a capture, tracking, and pointing testbed.

The forward body consists of the primary mirror, secondary mirror, and metering truss and is isolated from the aft body to minimize transfer of disturbances, and is rotated for retargeting. This general arrangement is also used for the Zenith Star configuration as shown in Figure 5.3.1.1 and the critical disturbances both thermal and dynamic are shown in Figure 5.3.1.2. Specific stiffness (E/density), thermal deformation resistance, damping, and weight are critical items. Dynamic response is driven by the high retargeting angular rotation, short settling time, and stringent pointing accuracy required. The Zenith Star system requirements have a common basis with the space-based laser. Root requirements have been developed by Lockheed and Martin Marietta as part of ongoing contract activities.

Identification and quantification of the Zenith Star requirements are essential steps in the structural evaluation of the metering structure. The definition and realization of meeting these requirements will demonstrate the viability of the metering structure for Strategic Defense Initiative (SDI) space structures. The Zenith Star requirements are separated into general categories of configuration and performance, as noted in Table 5.3.1.1.

Configuration requirements are imposed in order to have the structure integrate with the rest of the beam expander subsystem of the optical payload element. This results in the diameter and overall length constraints noted. The gross geometry is determined by the maximum payload diameter inside the Titan IV A payload fairing and by specification of the distance from the primary mirror vertex to the secondary mirror vertex. The obscuration requirement of a 5 in maximum leg cross section (including insulation, etc.) limits the size of the leg structure cross section.

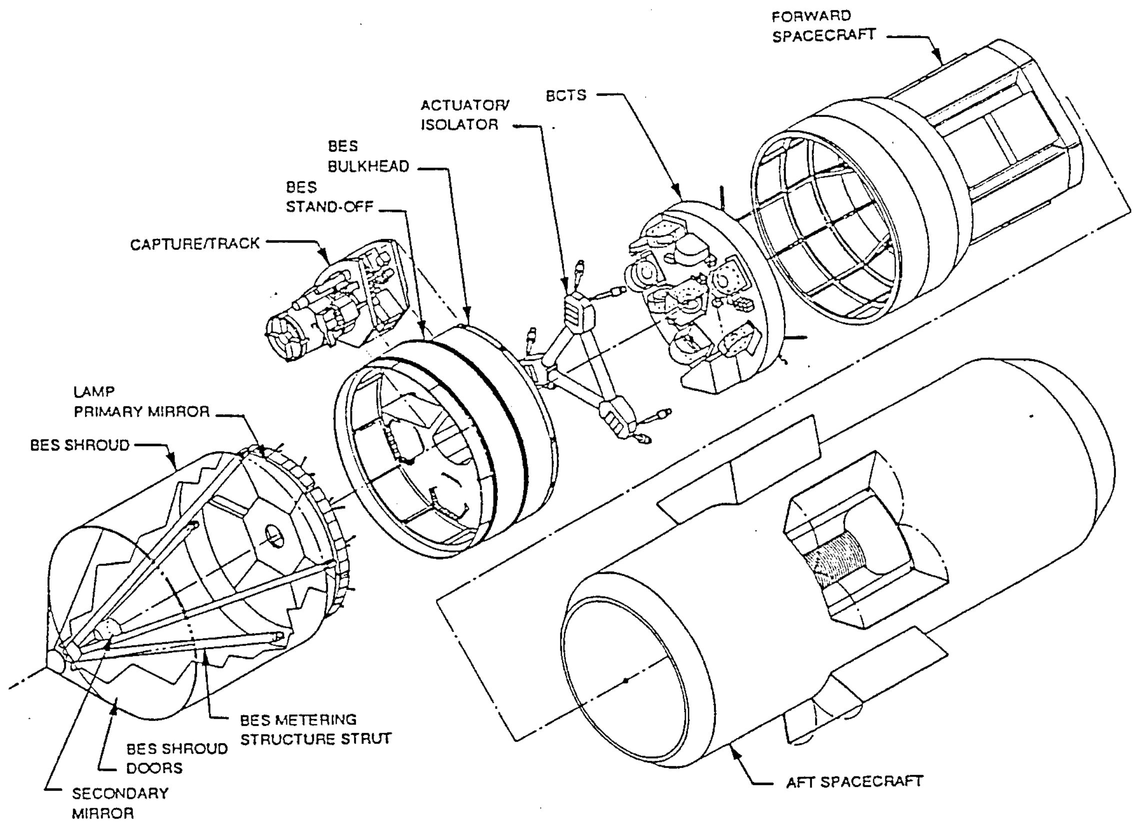


Figure 5.3.1.1 Zenith Star Configuration

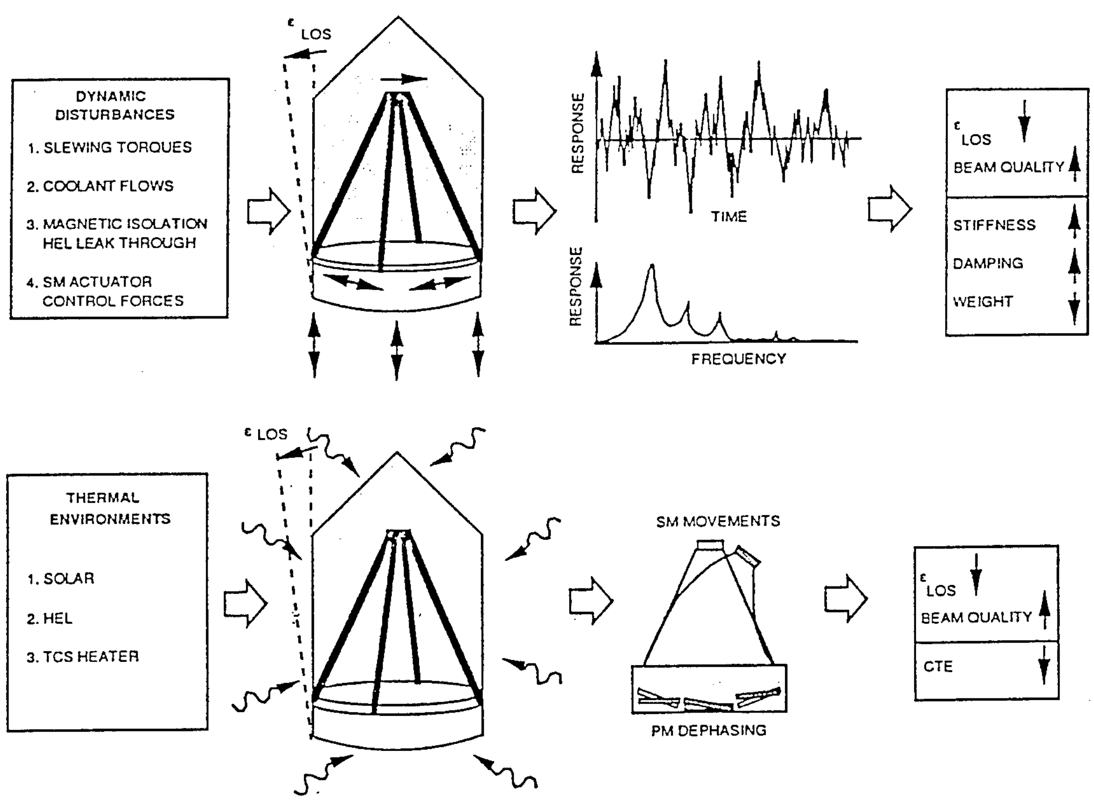


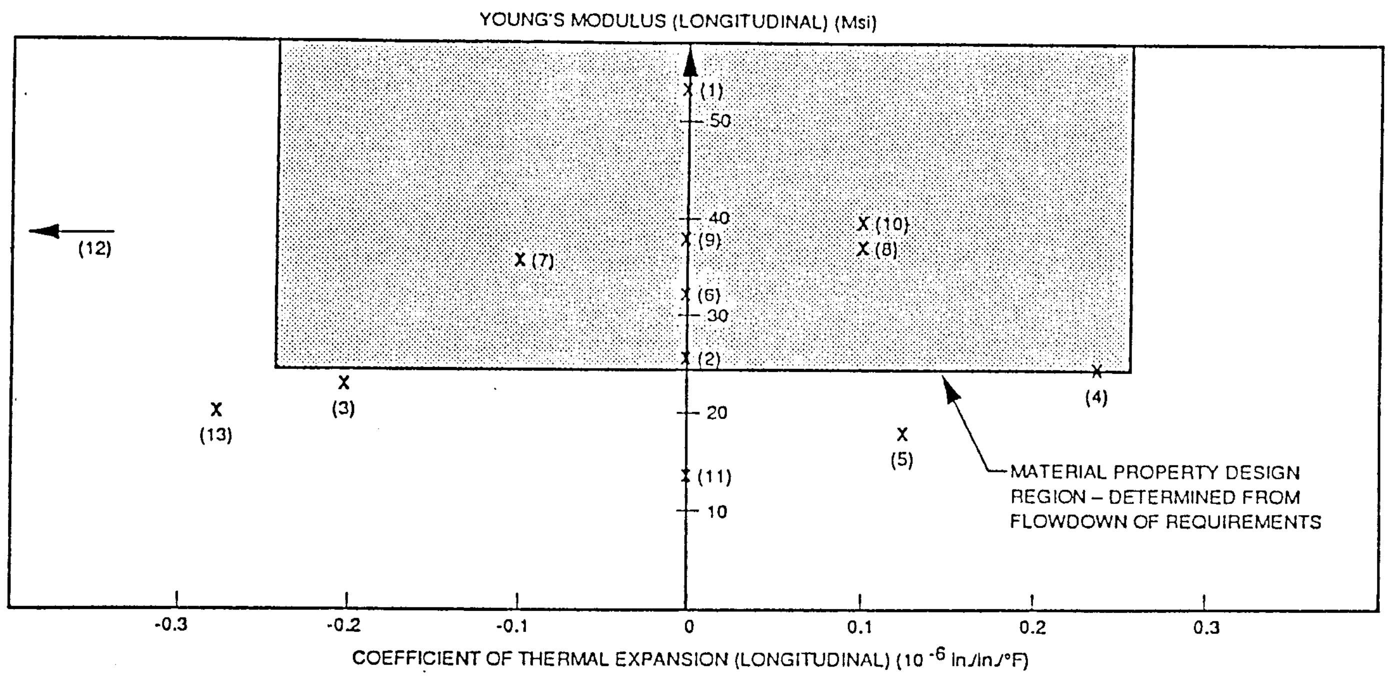
Figure 5.3.1.2 Thermal and Dynamic Disturbances

ITEM	REQUIREMENT	SOURCE/COMMENTS
CONFIGURATION		
ENVELOPE	MAX 176.90 in DIA AT BASE RING MAX 172.63 in DIA AT APEX MAX 206.2 in LENGTH	DIA LIMITED BY TITAN FAIRING DIA AND DYNAMIC CLEARANCE REQUIREMENT CONTROLLED BY IFA DESIGN CRITICAL DIMENSION IS PRIMARY MIRROR VERTEX TO SM VERTEX LENGTH
OBSCURATION	MAX 5 in. CROSS-SECTION PRESENTEDTO LASER BEAM, EACH STRUT (INCLUDES REFLECTIVE MATERIALAND MLV THERMAL SYSTEM)	OPTICAL/LASER POWER REQUIREMENT
PERFORMANCE		
WEIGHT	MAX 1300 lb. FOR METERING STRUCTURE AND STANDOFF STRUCTURE (CONNECTS METERINGSTRUCTURE TO BULKHEAD)	MASS PROPERTIES ALLOCATION FLOWED DOWN FROM TITAN IV LAUNCH CAPABILITY
STIFFNESS	16 HZ FIRST BENDING MODE (STANDOFF STRUCTURE INCLUDED,FIXED AT BULKHEAD INTERFACE)	MINIMUM GOAL, BASED ON 8X MAGNITUDE GREATER STIFFNESS DESIRED COMPARED TO CONTROL SYSTEM RESPONSE TO DISTURBANCES VS. OPTICAL ERROR BUDGET IS CRITICAL ITEM
DIMENSIONAL STABILITY	DEFOCUS: $\pm 2.5\mu$ DECENTER: $\pm 18\mu$ TILT: $\pm 11\ \mu rad$	REQUIREMENTS LISTED ARE THERMAL DISTORTION PORTION OF ERROR BUDGET FOR DISTORTIONS AFTER CALIBRATION TEMPERATURE DIFFERENTIAL DEPENDENT ON TYPE OF THERMALCONTROL
OUTGASSING	$\leq$1% TOTAL MASS LOSS	NASA JSC SP-R-0022A TESTED PER ASTM E595-84
DAMPING	1% CRITICAL (SYSTEM GOAL)	ENGINEERED PASSIVE AND/OR ACTIVE DAMPING TREATMENT MAY BE REQUIRED EXTENT OF DAMPING REQUIRED DEPENDENT ON RESPONSE LEVELS
STRUCTURAL INTEGRITY	MAINTAIN INTEGRITY OF STRUCTURE THROUGH CRITICAL LIFT-OFF PHASE WITH REQUIRED FACTORS OF SAFETY - DEMONSTRATE BY ANALYSIS AND ITEST	SEE LOADS FIGURE

Table 5.3.1.1 Zenith Star metering structure requirements.

Performance requirements ensure that all lift-off and on-orbit performance goals are met. For lift-off, the weight must be within the mass budget allocation. Weight is a critical item that must be constantly monitored.

The structure must maintain its integrity during lift-off so that on orbit operations can be successfully performed. The critical stresses occur during lift-off; the preliminary loads used for analysis are defined in Table 5.3.1.2.



LEGEND				REFERENCE
(1)	P100	Gr/Mg, [0],	50 V/O	a.
(2)	P100	Gr/Al, $[\pm 26]_s$,	43.5 V/O	a.
(3)	P75	Gr/Ep, [0/90 /0],	60 V/O	a.
(4)	P75	Gr/Mg, $[\pm 20]_s$,	40 V/O	b.
(5)	P75	Gr/Mg, $[\pm 30]_s$,	40 V/O	b.
(6)	P75	Gr/Mg, $[\pm 16]_s$,	48.2 V/O	b.
(7)	P100	Gr/Aℓ, $[\pm 20]_s$	43 V/O	c.
(8)	P100	Gr/Aℓ, [±20/0/±20],	43 V/O	c.
(9)	P100	Gr/Mg, $[\pm 12]_s$,	40 V/O	c.
(10)	P100	Gr/Mg, [±12/0/±12],	40 V/O	c.
(11)	P75S	Gr/Ep, $[0/\pm 45/90]_s$,	52 V/O	c.
(12)	P75S	Gr/Ep, [0],	52 V/O	c.
(13)	P100	Gr/Ep, $[0/\pm 60]_s$,	60 V/O	d.

REFERENCES	
a. F33615-78-C-5235	FINAL TECHNICAL REPORT, FEB 1984, LMSC-D885477
b. N000-84-C-5306	FINAL REPORT, OCT 1988, MMAG-MCR-88-635
c. F33615-81-C-5128	FINAL REPORT, JAN 1987, UTRC-R86-980762
d. CALCULATED BY LAMINATE THEORY	

Figure 5.3.1.3 Available CTE and Modulus

Once the spacecraft has been placed in orbit the stability of the support structure for optical experiments becomes a vital concern. Stringent outgassing limits are needed to prevent depositing of contaminants on optical surfaces. Sources of error following calibration that affect optical quality must be identified and error budgets allocated to ensure final beam quality. Some sources of error include:

1- Thermal distortions of structure,

2- Dynamic disturbances:

-Coolant flow (pumps within forward spacecraft),

-Disturbance transmittal across isolation system from aft spacecraft,

3- Distortion of cooled mirrors induced by thermal and coolant pressure,

4- Moisture desorption induced structural distortions.

The thermal distortions are dependent on the thermal environment, coefficient of thermal expansion (CTE) , and structure geometry. The thermal environment must be determined through analysis. The portion of the optical error budget allocated to thermal distortions has been quantified and is shown in Figure 5.3.1.3. Flowdown of this deformation requirement to a material CTE can only be made for a specific structural configuration and thermal environment. Finite element sensitivity studies were used to identify the range of acceptable CTE for the struts based on an assumed +2°F uniform structure heating. The range identified was 0 to 0.2 ppm/°F. Phase One analysis will confirm this selection.

EVENT	AXIS	STEADY STATE (g)	VARIATION (g)	TOTAL MAX/MIN
LIFTOFF	AXIAL LATERAL TORSION	1.5C 0 0	± 1.0 ± 2.5 ± 0.03/in	0.5 C to 2.5 C ± 2.5 ± 0.03/in
STAGE 1 BURNOUT (MAX. AXIAL)	AXIAL LATERAL	0.0 TO 4.0 C 0	± 1.5 ± 1.0	1.5 TO 5.5 C ±1.0

1. T = TENSION, C = COMPRESSION
2. LATERAL LOAD DISTRIB. VARIES WITH DISTANCE (X) FROM SPACECRAFT/LAUNCH VEHICLE INTERFACE:*
   G(X) =(3/5) (X/Xcg) + (2/5) Gcg
   X = DISTANCE FROM STRUCTURE LOCATION TO SPACECRAFT/LAUNCH VEHICLE INTERFACE
   Xcg = DISTANCE FROM THE SPACECRAFT/LAUNCH VEHICLE INTERFACE TO SPACECRAFT CG**
   Gcg = LOAD FACTOR FROM TABLE ABOVE
3. UNCERTAINTY FACTOR = 1.3 INCLUDED

*SPACECRAFT/LAUNCH VEHICLE INTERFACE AT X = 997 in
**SPACECRAFT CG AT X = 1211 in (PRELIMINARY)

Table 5.3.1.2 Preliminary Zenith Star Structure Limit Loads

For the purposes of preliminary assessment of the metering structure performance, the disturbance response requirement has been quantified in terms of the first bending mode frequency of the structure. An early goal of 20 Hz was established in order to size structural members. The 20 Hz value was selected solely due to a desire to have the metering structure fundamental frequency separated from the secondary mirror focus control loop bandwidth by an order of magnitude. This ensures that the reaction forces of the secondary mirror control will not interact with the structural dynamics, introducing any additional errors.

5.3.1.3 Flow-Down to SPICE

The Zenith Star spacecraft offers one of the most demanding challenges to advanced materials for mission performance and reliability requirements. The Zenith Star system will be required to maintain ultra-precision alignment and dimensional stability in the presence of dynamic and thermal disturbances (see Figure 5.3.1.2). Conventional materials and structures technologies do not provide adequate stiffness and/or thermal response to maintain this level of precision. However, metal matrix composites which possess combinations of high specific stiffness, near-zero CTE, and high thermal conductivity, provide the necessary characteristics to produce light-weight, stiff, and dimensionally stable structures that can meet the performance goals of SDI missions.

The metering structure design concept for Zenith Star is a quadrapod beam expander as shown in Figure 5.3.1.4. The SPICE structure is a tripod beam expander whose basic geometry is approximately forty percent larger. This difference does not significantly affect the results of an advanced composite material task. The plan is to make the cross-section of the legs as shown in Figure 5.3.1.4 while increasing the length to match the geometry of SPICE. This does not affect the primary objectives because the producibility, reliability, flight qualification, and space qualification issues are addressed at the leg level. The performance requirement is demonstrated in the precision pointing experiment. This validates the design process which then is scalable to the geometry of Zenith Star. The advantages of using composites is that the material can be tailored to meet diverse requirements. Several parameters are available including fiber volume, fiber modulus, fiber orientation, matrix material, and the number of layups. A graphic comparison of P75 (P is the type of fiber and 75 refers to the modulus) and P100 Gr/Ep, Gr/Mg (Graphic/Magnesium), and Gr/Al (Graphic/Aluminum) for selected layups and fiber volumes help illustrate the range of CTE and modulus available (see Figure 5.3.1.5). The projected range of acceptability for these properties, derived by analysis, is identified by the shaded rectangle. This illustrates that conventional Gr/Ep composite designs cannot meet both the modulus requirement and CTE requirement simultaneously. Material configurations 11, 12, and 13 can meet either the modulus requirement or the CTE requirement but not both. The only acceptable candidates are either Gr/Mg or Gr/Al.

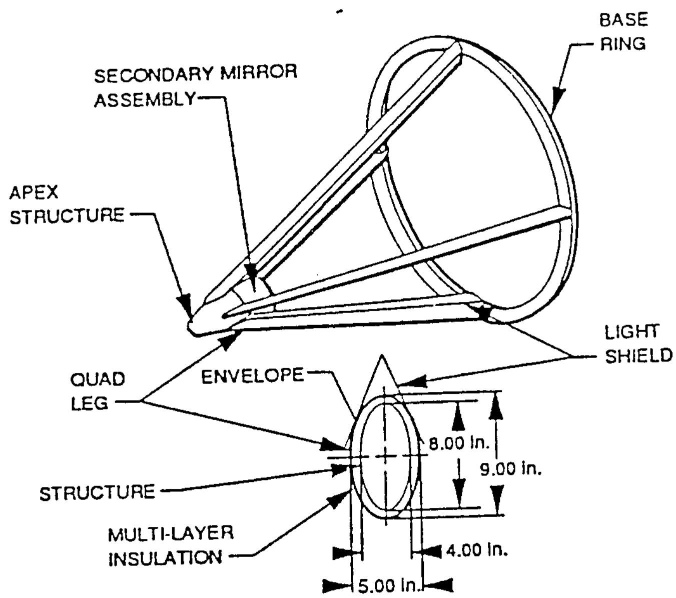


Figure 5.3.1.4 Metering Structure Design Concept

DESCRIPTION	1990 (1 2 3 4)	1991 (1 2 3 4)	1992 (1 2 3 4)	1993 (1 2 3 4)	1994 (1 2 3 4)
PHASE 1 DESIGN, SUPPORTING ANALYSIS, AND PROCUREMENT OF LONG LEAD MATERIALS	▲	15 Months	▼ CDR		
PHASE 2 FABRICATION OF STRUTS			▲ 15 Months	▼	
PHASE 3 COUPON TESTING AND COMPONENT TESTING				▲ 6 Mon ▼	
PHASE 4 SPICE INTEGRATION MODAL TESTING AND PRECISION POINTING EXPERIMENT				▲	7 Mon ▼

Figure 5.3.1.5 Advanced Composite Material

P75 Gr/Mg has been selected as the baseline material for the metering structure struts. A P100 or P120 fiber would provide better performance, but the significant increase in cost of these fibers is not in proportion to the incremental improvement in performance. The specific fiber selection will be reviewed in Phase One. The 75/Mg will result in a 15 Hz stiffness; response levels could be reduced by damping treatments.

5.3.1.4 Conceptual Design

The basic Advanced Composite Materials Task includes the fabrication of the three main tripod legs and performing extensive ground testing to ensure that they are flight qualifiable. The experiment is logically divided into four phases:

1- Design, supporting analysis, and procurement of long lead materials (e.g. fibers)

2- Fabrication of the struts.

3- Coupon and component testing.

4- SPICE integration, modal test, and precision pointing experiment.

Data reduction and model comparisons are then made for final performance validation of the advanced materials. This process then validates the advanced materials as flight qualified and as meeting the performance requirements.

COMPONENT		NON-DESTRUCTIVE EVALUATION			TAG ENDS	
	QUANTITY	X-RAY	DIMENSION	ULTRASONIC MODULUS	FIBER VOLUME	PHOTO-MICROGRAPH
STRUTS	12	12	12	12	48	48
STRUT SPLICES	8	8	8	8	16	16

Table 5.3.1.3 Number of advanced materials coupon tests.

In Phase One, the details of the strut designs will be accomplished. Some coupon tests will be performed in Phase One to support the design effort. During Phase Two, the struts will be fabricated. In Phase Three, reproducibility, repeatibility, and reliability are addressed by performing a matrix of coupon tests and component tests on the delivered tubes and splices that will be assembled into advanced materials tripod struts. The numbers of the various kinds of coupon tests are shown in Table 5.3.1.3. Each strut consists of several lengths of tubes spliced together. The tubes and splicing elements are subjected to the same battery of tests. Strength and modulus tests will be performed on the strut assemblages (full

length) to insure that each strut meets the stiffness and launch load requirement. In Phase Four the integration of the advanced materials struts into the SPICE apparatus will be done followed by modal testing and a precision pointing experiment. The same experiments will have already been performed on the Precision Pointing Experiment Subtask using the current tripod legs. Comparison of the results of the two sets of experiments will provide an assessment of the effects of the use of the advanced materials on performance.

Due to the large size of this structure, the magnitude of the effort required to perform full scale thermal distortion testing is prohibitive. The plan is to perform CTE tests at the coupon and component levels. The struts (full length) will be subjected to a temperature change from +40°C to 0°C and then back to room temperature. The CTE test results from these component and coupon tests will be used to analytically predict the thermal distortion of the full beam expander structure. The results of this analysis will be compared to the flowed down requirements.

5.3.1.5 Determination of SPICE Adequacy

As implied in other parts of the discussion of this experiment, the SPICE apparatus is suitable for performing this experiment. The only modification required is the addition of the advanced materials elements to be tested.

5.3.1.6 Additional Hardware/Software/Facilities

Three composite materials tripod legs will be required.

5.3.1.7 Cost Estimates

The cost estimate in $K is broken down into labor, material, and subcontracts categories by experiment phase as shown in Table 5.3.1.4. This estimate including material, subcontracting and labor is based on a similar advanced composite material proposal for the Zenith Star struts prepared this fiscal year.

	Phase One ($K)	Phase Two ($K)	Phase Three ($K)	Phase Four ($K)
Labor	1680	1169	773	340
Material	112	2	6	2
Subtotals	1792	1171	679	342
Total	$3.984 M			

Note: The total does not include any fee, management overhead, or travel costs.

Table 5.3.1.4 Cost Estimates for the Advanced Materials Experiment

5.3.1.8 Schedule Estimates

The advanced composite material task is divided into four phases as shown in Figure 5.3.1.5.

5.3.1.9 Benefits to Zenith Star

The primary benefit to Zenith Star is that the insertion of advanced composite materials permits the beam expander to meet its frequency and thermal distortion performance requirements. Without the use of advanced composite materials, performance requirements would need to be relaxed. This would result in added burden to other components, such as increased dynamic range and bandwidth for the fast steering mirror, secondary mirror, and deformable mirror.

In addition there are several secondary benefits:

- Lower weight - less thermal insulation (10% less)
- Increased Thermal Conductivity (50% greater)
- Lower CTE (Factor of 5)
- No moisture Absorption problems
- No outgassing

The successful completion of this task qualifies this material for a space satellite program. This means that these materials are viable candidates to be included in a material trade.

The final task in Phase Four will include a fully documented assessment considering the applicability, readiness, and cost of using advanced materials. The advanced material design will be compared to the baseline Gr/Ep design and to an Aluminum design. Recommendations will be based on a cost to performance tradeoff.

5.3.2 Passive Damping Systems for Tripod Modes

5.3.2.1 Objective

The objective of the proposed task will be to investigate the use of passive damping to reduce the response of vibration modes of the Zenith Star and ALI metering structures (quadrapod).

5.3.2.2 Zenith Star Requirement

Neither the structural configuration nor the disturbance environment of an actual Zenith Star spacecraft are well defined. Consequently no quantitative requirements for passive damping can be derived at present. It is apparent, however, that passive damping is one of the potential contributors to reduction of Zenith Star beam expander vibration and therefore, to better output beam quality. The requirement for passive damping of beam expander modes flows from the high-priority target engagement requirements of Zenith Star. In addition, it has recently become apparent that ALI will require passive damping of its quadrapod.

5.3.2.3 Flow-Down to SPICE

An important similarity between the Zenith Star and SPICE structures is that both are designed around cassegrain optics. A large primary mirror and smaller secondary mirror face each other with both supported off a structural bulkhead. The primary mirror mounts directly to the bulkhead and the secondary mounts via a metering structure: a tripod in SPICE and a quadrapod in Zenith Star. In both cases the long legs of the metering structure produce low-order vibration modes which have important effects on optical performance. Damping of these modes is highly desirable.

Damping of tripod modes is being specifically addressed within the Precision Pointing Experiment of SPICE. In particular, constrained-layer viscoelastic treatments and tuned-mass dampers are being designed. However, the SPICE and Zenith Star metering structures are dynamically quite different; it is unlikely that damping systems designed for one could be directly applied to the other.

This section describes an effort by which the damping concepts being developed for the SPICE metering structure could be redesigned for use in Zenith Star.

5.3.2.4 Conceptual Design

5.3.2.4.1 Constrained-layer Viscoelastic Dampers for Tripod Modes. Modes involving bending of long prismatic members are good candidates for damping by means of constrained viscoelastic dampers. However, the optimum choice of viscoelastic material and geometry is highly dependent on the properties of the base structure, i.e., the undamped legs of the metering structure. Length, cross section, base material properties, and end conditions all affect the damping design.

A useful application of SPICE resources in this case would be in the area of analytical design of a constrained-layer damping system for the Zenith Star quadrapod. This would assess the potential benefits but would not impact near-term Zenith Star activities. It would use the expertise of the SPICE team but not the SPICE apparatus.

The study would require a finite element model of the Zenith Star primary structure. Accurate dimensional detail would be required only for the quadrapod legs and secondary mirror support structure. Modeling of the primary support bulkhead and other structural elements could be fairly coarse. Existing models developed within Zenith Star could probably be adapted for the purpose. The modal strain energy method implemented in NASTRAN would be used along with a number of specialized post-processors developed by CSA Engineering for damping design.

Results of the study would be a recommended damping configuration (viscoelastic material, constraining-layer material, and geometry) as well as predicted values of damping for the most important quadrapod modes.

5.3.2.4.2 Tuned-Mass Dampers for Tripod Modes. tuned-mass dampers are inherently modular, add-on devices. A tuned-mass damper is usually designed to damp only one or a small number of modes in a narrow frequency range. As such, its design depends only on properties of the target modes. However, these properties, particularly natural frequencies, are quite different between the SPICE and Zenith Star structures. Additionally, the issue of the qualification for space is of much more immediate interest to Zenith Star than to SPICE.

Like constrained-layer dampers, the best short term use of SPICE resources for Zenith Star would probably be in terms of an analytical study. It would determine an optimum tuned-mass damper

configuration for the Zenith Star metering structure. The study would use a somewhat simplified version of the finite element model described in Section 5.3.2.4.1. Results would be in terms of predicted damping ratios for tripod modes versus added weight and assumed tuning accuracy of the tuned-mass damper. If desired, this analytical design could be taken further to the point of layout drawings, selection of candidate damping materials, and design for packaging the tuned-mass dampers in a space-qualified configuration.

5.3.2.5 Determination of SPICE Adequacy

The tasks described herein make use of SPICE in that the SPICE team and synergistic interaction with the Precision Pointing Experiment Design Subtask (02-03) are the key ingredients to its success. Therefore, the SPICE Program capabilities are exactly what is required.

5.3.2.6 Additional Hardware/Software/Facilities

The model extensions described above will require the development of some software interfaces between existing codes, and some specific finite element model construction. Otherwise, no additional resources are required.

5.3.2.7 Cost Estimates

Total cost of the passive damping of tripod/quadrapod modes study is estimated to be $55K.

5.3.2.8 Schedule Estimates

The estimated calendar time for this experiment is 4 months.

5.3.2.9 Benefits to Zenith Star

The benefits to Zenith Star of passive damping will be typical of other aerospace applications of the technology. Reduction of resonant response through damping will allow better pointing accuracy, faster retargeting, lighter weight, etc. This effort will provide designs of viscoelastic and tuned-mass dampers for Zenith Star with the designs informed by the experience gained from the Precision Pointing Experiment Subtask of SPICE. This will provide better options when the inevitable choices must be made between damping and other performance measures such as weight, cost, complexity, etc., for an actual Zenith Star spacecraft.

A more immediate benefit of SPICE passive damping investigations may accrue to ALI. Zenith Star and SPICE personnel have already discussed the possibility of SPICE assisting ALI in meeting its need for damping of vibrations in its quadrapod metering structure.

5.3.3 Passive Damping for Mirror Mounts

5.3.3.1 Objective

The objective of the proposed task will be to investigate the use of passive damping in the interface structure (struts) used to mount mirror segments to their backup structure.

5.3.3.2 Zenith Star Requirement

Neither the structural configuration nor the disturbance environment of an actual Zenith Star spacecraft are well defined. Consequently no quantitative requirements for passive damping can be derived at present. It is apparent, however, that passive damping is one of the potential contributors to reduction of Zenith Star mirror mount vibration and therefore to better output beam quality. The requirement for passive damping of beam expander modes therefore flows from the high-priority target engagement requirements of Zenith Star.

5.3.3.3 Flow-Down to SPICE

Primary mirror segments of a space-based laser are likely to be mounted from a backup structure by discrete-struts, either active or passive. An important group of normal modes will be those involving motion of the mirror segments, either flexing or moving as rigid bodies on the compliance of the struts. Such modes will be important contributors to both line of sight and wavefront error. They are natural targets for passive damping.

In the case of Zenith Star, the LAMP mirror segments are effectively rigid compared to their supporting struts. Normal modes in which the mirror segments move as rigid bodies are predicted to occur as low as about 30 Hz, compared to over 800 Hz for flexural modes. This implies that the struts are good candidates for passive damping but the mirrors themselves are not.

As currently configured, the SPICE structure includes mirror simulators that are designed to be essentially rigid relative to the low order, global modes of the supporting truss. This is qualitatively similar to Zenith Star although the absolute frequency values are quite different. The first global system mode is at about 8 Hz. Unlike an actual space-based laser system, the SPICE simulated mirror petals all lie in a common plane. They are hard-mounted to the mirror deck of the truss bulkhead without any interface structure such as struts, either active or passive.

This section describes, at the conceptual level, an experiment whereby the resources of SPICE are used to investigate passive damping of mirror modes as defined above.

5.3.3.4 Conceptual Design

The investigation will use both the SPICE apparatus and the specialized expertise of the SPICE team in the area of passive damping. The end result will be a demonstration of a damping system designed specifically to reduce the response of mirror modes.

The damping investigation will consider both passive and active mirror struts. For a passive strut, damping would take the form of viscoelastic or viscous elements either in series or in parallel with the load-carrying strut. For an active strut, the damping element would be only in parallel. In either case, the main questions are:

1- Where should the dampers be located? It may not be necessary or desirable to damp every strut.

2- What combination of damper stiffness and loss factor produces the greatest improvement in line of sight performance?

3- What level of damping can be obtained and what does this level translate to in terms of line of sight improvement?

The steps of the investigation would proceed as follows. Verified finite element models of the SPICE truss and mirror simulators are assumed to be available.

1- Select/design struts. Realistic designs for active or passive struts would be developed in consultation with Zenith Star. They would be designed to locate the SPICE outer-petal mirror simulators in a way that is consistent with the expected focal length of an actual primary mirror sized for the SPICE truss. Mounting of the center-petal simulator could probably be kept as is.

2- Determine strut stiffness. Axial stiffness of the struts would be determined, either by analysis or by fabrication and test. In the case of an active strut, the control system state corresponding to the relevant stiffness would be determined based on the nature of the control system.

3- Update finite element model. The model will be reworked to include the strut-mounted configuration of the outer-petal mirror simulators.

4- Determine damper geometry. Realistic damper configurations will be identified. "Realistic" in this context implies an arrangement that locates the viscoelastic or viscous elements in series or parallel with the main load path depending upon what is appropriate and practical to build.

5- Perform design analysis. Analytical representations of the damping element will be added to the finite element model. The dynamic properties of the damper elements will then be optimized. Criteria will be damping of optically significant modes and line of sight error under typical dynamic

load conditions. The primary analysis methods will be modal strain energy for viscoelastic elements and complex eigenvalues for viscous elements. It is likely that advanced, high-stiffness materials would be recommended for structural elements that are in series with the dampers. This tends to concentrate strain energy in the damping elements for maximum damping.

6- Fabricate struts and dampers. The optimized damped struts will be fabricated and tested at the component level. Measured complex stiffness of the struts with dampers will be obtained and compared to analytical predictions. This provides an important early benchmark for the design analysis. If possible, undamped struts that are interchangeable with the damped units will be built for later comparisons.

7- Reconfigure SPICE truss. The outer-petal mirror simulators will be removed from the SPICE truss, modified as necessary, and reinstalled with damped-strut mounting. The segments will be canted inward towards the optical axis to simulate a primary mirror of finite focal length . The OSS will be reconfigured as necessary to allow operation with the new mirror segment positions.

8- Test truss with damped mirror mounts. Final system-level tests will be performed. The OSS will be used to measure line of sight error in the same way it is currently being used in the Precision Pointing Experiment. This quantity will be measured under simulated operating dynamic loads with damped and (if possible) undamped mirror mounting struts. Modal damping ratios for optically significant modes will also be measured under artificial excitation.

5.3.3.5 Determination of SPICE Adequacy

The SPICE apparatus will be fully adequate to perform this experiment once the modifications to the primary mirror segments described above have been done.

5.3.3.6 Additional Hardware/Software/Facilities

Hardware: Dampers and struts described above.

Software: Updates to Zenith Star, SPICE finite element models.

5.3.3.7 Cost Estimates

Table 5.3.3.1 shows the estimated costs for design and performance of the passive damping of mirror mount modes.experiment.

	Experiment Design ($K)	Experiment Performance ($K)
Labor	40	60
Materials	Fabrication	0
Subtotals	40 plus Fabrication	60
Total	**$100K plus Fabrication**	

Table 5.3.3.1 Passive Damping of Mirror Mount Modes Experiment Cost Estimates.

5.3.3.8 Schedule Estimates

The estimated calendar time for this experiment is 6 months.

5.3.3.9 Benefits to Zenith Star

The benefits to Zenith Star of passive damping will be typical of other aerospace applications of the technology. Reduction of resonant response through damping will allow better pointing accuracy, faster retargeting, lighter weight, etc. The practical benefit of pursuing the development through SPICE comes from the fact that SPICE is a ground test facility, and yet is fairly realistic in terms of structural dynamics. Damping systems specific to the structural features of a space-based laser can be developed and ground tested quite rapidly. This experiment will directly demonstrate the advantage of using properly designed passive damping on the mirror mounts of the SPICE testbed. The global modes of SPICE and Zenith Star are different, so further analysis will be needed to generate a Zenith Star design of this type. However, the advantages to be expected from it will already be established by this experiment. This will provide better understanding of options when the inevitable choices must be made between damping and other performance measures such as weight, cost, complexity, etc., for an actual Zenith Star spacecraft.

5.4 Disturbance Characterization

Three experiment conceptual designs are discussed that address the characterization of the degradation of the wavefront and line of sight due to disturbances arising from coolant flow in a cooled secondary mirror. Two methods of approach to the problem are presented: admittance modeling and direct computation from fluid dynamical equations. In the former, measurements are used in conjunction with theory to characterize the forces experienced by the structure due to the coolant flow; the connection forces are derived from measurements and theory. The second approach is more basic but does not appear to be able to solve the entire problem yet. It was judged to be a sensible approach to this problem to advocate a procedure that can be used in the near term and one that gives promise farther out.

5.4.1 Mirror Coolant Flow Disturbance Characterization by Admittance Modeling on a Passive Structure

5.4.1.1 Objective

The objective of this experiment is to provide a means of predicting the effect upon the Zenith Star structure of forces arising from the flow of liquid coolant through a cooled secondary mirror. In this experiment, the method of admittance modeling is validated on SPICE without active structural control being employed. The Zenith Star structure is not at present expected to be actively controlled.

5.4.1.2 Zenith Star Requirements

In the ALI ground test, the structural disturbance due to coolant flow to and within the secondary mirror has been identified as requiring better characterization than is now available. The Zenith Star is required to place a high intensity beam on distant targets. Therefore, it must project a beam from its beam expander that has low jitter and good wavefront quality. The system must be designed so that the sources of disturbance that induce vibration into the structure do not produce distortions in the optical train that degrade the beam below the performance criteria. Vibration suppression techniques will necessarily be employed to reduce the effects of the disturbances upon the outgoing laser beam. The selection of the parameters of disturbance suppression techniques must be guided by accurate information about the magnitude and character of the disturbances. Provision of a method for accurately characterizing the effect upon the outgoing HEL beam of coolant flow in a cooled optical element is a Zenith Star requirement that derives from the target engagement goals of Zenith Star. Furthermore, rapid retargeting and active tracking require jitter control which in turn implies a requirement that major sources of jitter be well characterized.

5.4.1.3 Flow-down to SPICE

Admittance modeling is to be used here to predict the effect upon a large complex passive structure of coolant flow through a mirror. The data needed are obtained from measurements made with coolant flowing through a rigidly mounted mirror surrogate and from calculations performed using the Zenith Star structural model. The SPICE structural model and existing structure can be used as a stand in for Zenith Star in verifying the characterization procedure. Measurements made with the cooled component actually mounted to the SPICE apparatus can demonstrate the validity of admittance modeling predictions on a large flexible structure. Validation of the method on SPICE is a major step toward demonstrating its quantitative applicability to Zenith Star.

5.4.1.4 Conceptual Design

Overview: The objective of this experiment is to demonstrate by experiment the use of admittance modeling for prediction of flow-induced vibration in a complex structure. The experiment will include the acquisition of sufficient data to predict the mount-point forces from the mirror when it is connected to either the SPICE structure or the Zenith Star structure (or any structure for which an accurate finite element model is available). Previously, characterization of a considerably simpler combined system (see Figure 5.4.1.1) response in this way has had reasonable success. Figure 5.4.1.2 shows the comparison between calculation from an admittance model and direct measurements.

Description of Experiment: Figure 5.4.1.3 is a diagram of the experimental and analytical procedure. The admittance model is obtained from three data sets.

1. The element to be tested, i.e., the surrogate secondary mirror with its fluid supply plumbing, is hard mounted to a rigid base at the points at which it would be attached to the Zenith Star or SPICE structure. Coolant is forced via a pump or a blowdown device from a cooling cart through the coolant flow channels in the surrogate optical element at pressures and flow rates of interest. The (three-dimensional) mount forces are measured using transducers at the attachment points and their auto- and cross-spectral densities are recorded.
2. With the fluid flow turned off and the mirror suspended free-free, artificial excitation of the mirror and fluid supply system permits measurement of the motion/force admittance matrix at the mount points.
3. The motion/force admittance matrix at the mount points of the structure that is to receive the cooled mirror is obtained using the finite element model. For the SPICE structure, this matrix could also be acquired from direct measurements, but it is desired to establish a paradigm that can be applied when the main structure is available only as a finite element model.

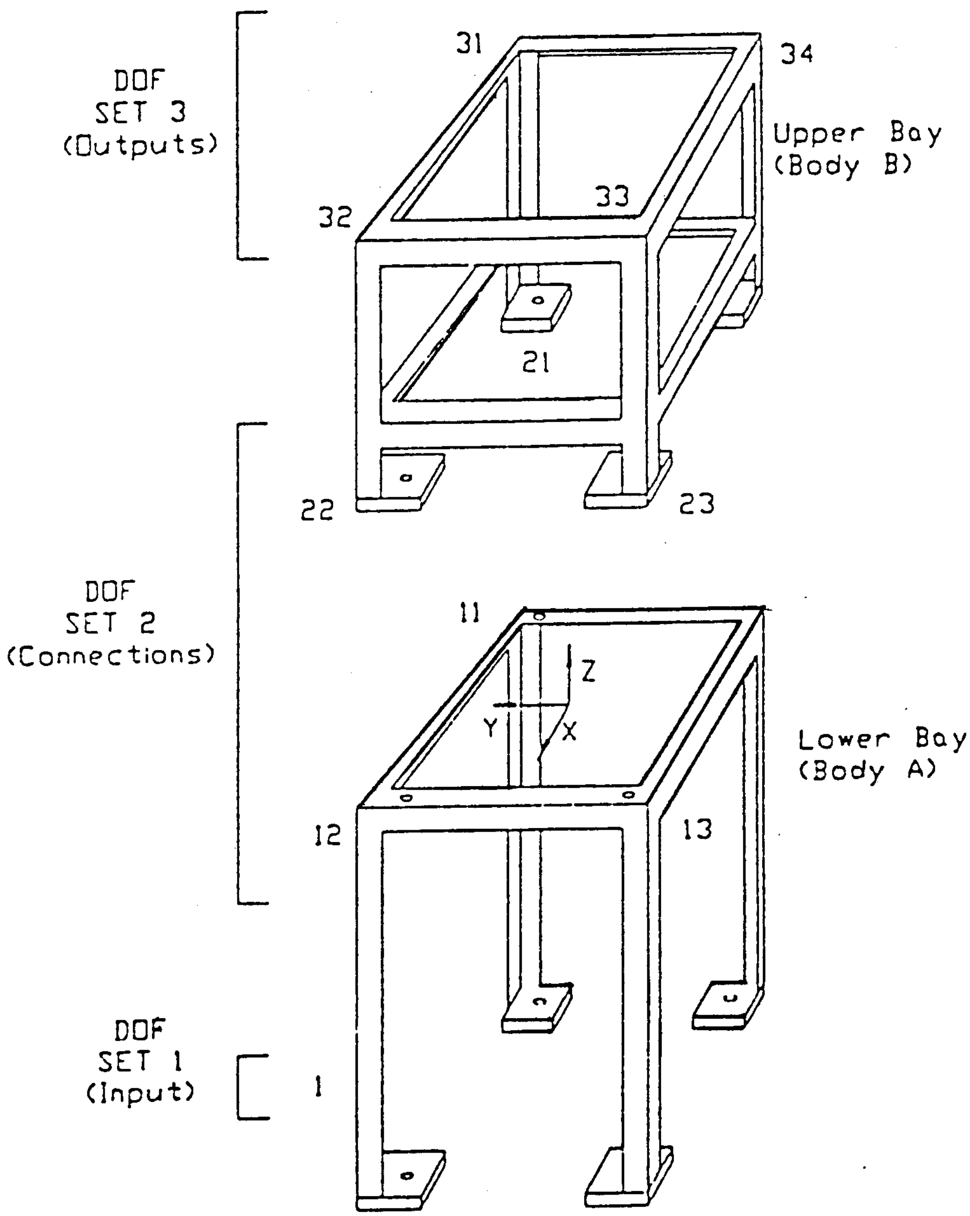


Figure 5.4.1.1 Characterization of Simpler Combined System

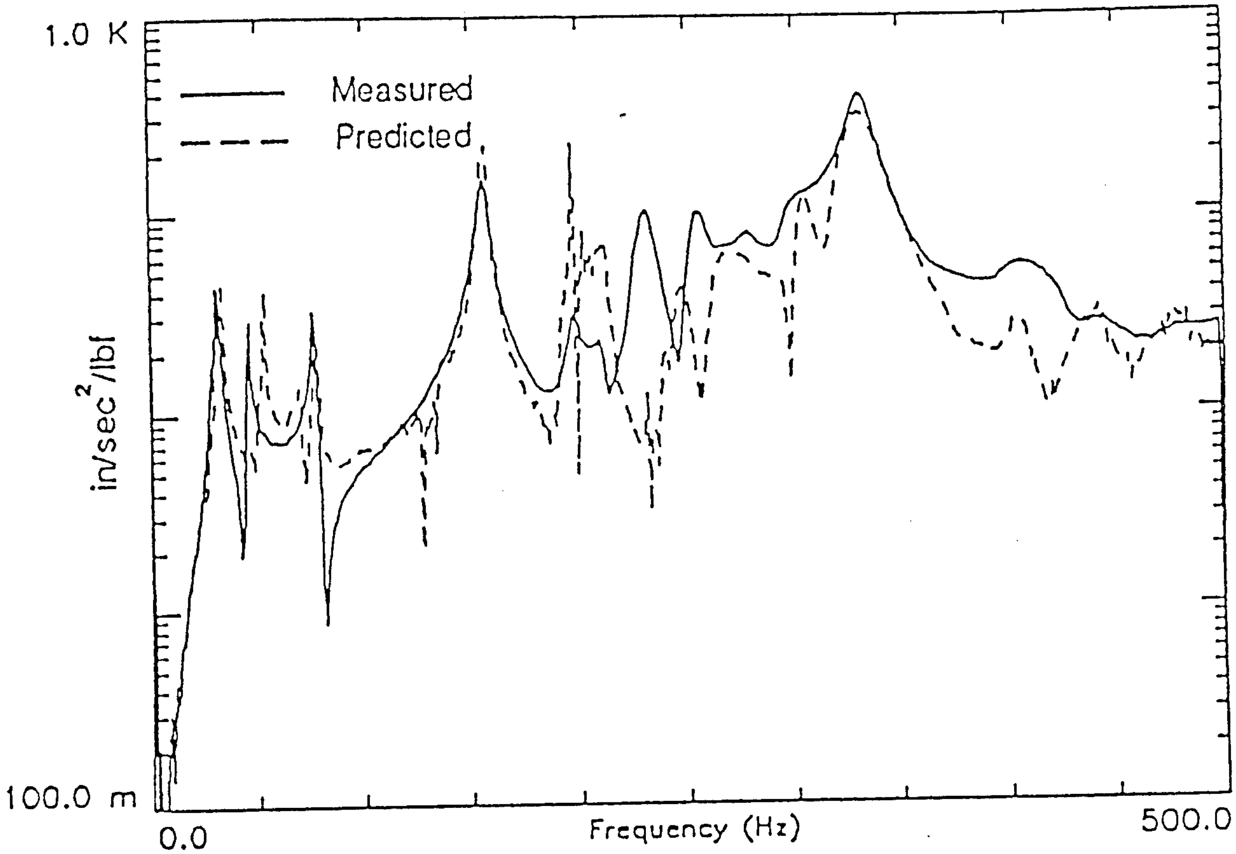


Figure 5.4.1.2 Comparison of Predictions to Measurements

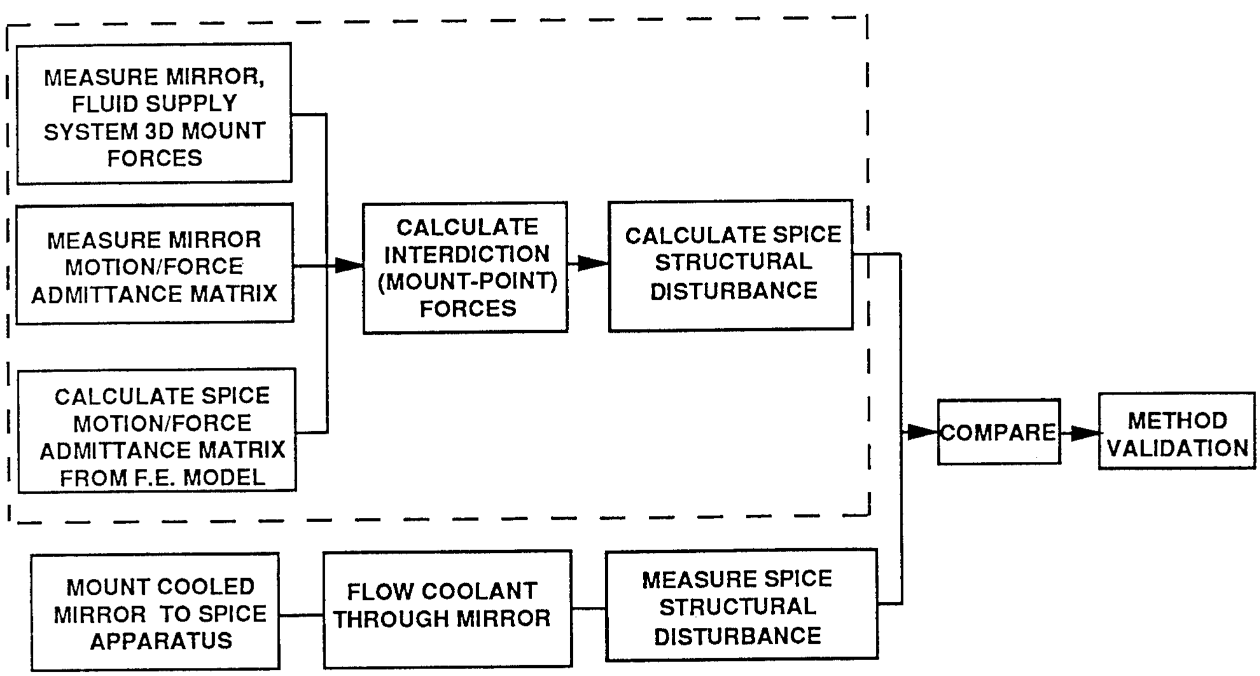


Figure 5.4.1.3 Experimental and Analytical Procedure

These data suffice to characterize the effect of the coolant flow disturbance on the SPICE structure. Direct measurements of the combined cooled mirror/SPICE apparatus system response are then made (with SPICE active structural controls not employed) and compared to those calculated from the system admittance model. With the method validated on SPICE, the effect of coolant flow in the same secondary mirror on the Zenith Star structure can be obtained by repeating the part of the procedure enclosed in the dashed box in Figure 5.4.1.3, with the Zenith Star structural model replacing that of SPICE. Note that the Zenith Star structure itself is not required, only its finite element model.

5.4.1.5 Determination of SPICE Adequacy

The SPICE structure needs only to be modified to permit attachment of the cooled secondary mirror surrogate. It is already an excellent stand-in for Zenith Star in this experiment.

5.4.1.6 Additional Hardware/Software/Facilities

The following additional hardware is required for this experiment to be performed on the SPICE apparatus:

1. A cooled secondary mirror surrogate.
2. A rigid base to which to mount the cooled element for admittance model data taking.
3. A cooling cart or equivalent.
4. Transducers and recording devices for the off-structure data gathering.

5.4.1.7 Cost Estimates

Characterization of mirror coolant flow disturbance by admittance modeling is an integrated effort. It is not meaningful to separate design and performance of the experiment. Table 5.4.1.1 shows the estimated costs for this experiment. The materials cost is for the secondary mirror surrogate.

	Experiment ($K)
Labor	140
Materials	FAB
Total	**140 + FAB**

Table 5.4.1.1 Admittance Modeling of Mirror Coolant Flow Disturbance Cost Estimates.

5.4.1.8 Schedule Estimates

The tasks in the cost schedule table require an estimated calendar time from start of experiment of 8 months.

5.4.1.9 Benefits to Zenith Star

Accurate characterization of coolant flow disturbances to the ALI and Zenith Star beam expanders will reduce risks on each of them. Tradeoffs concerning jitter and wavefront error suppression techniques and parameters will have accurate quantitative information about a major source of distortion that is, at present, only semiquantitatively characterized.

The method proposed is sufficiently flexible that future changes to the Zenith Star structural design will not require further coolant flow characterization experiments.

5.4.2 Mirror Coolant Flow Disturbance Characterization by Admittance Modeling on an Active Structure

5.4.2.1 Objective

The objective of this experiment is to provide a means of predicting the effect upon an actively controlled structure of forces arising from the flow of liquid coolant through a cooled secondary mirror. In this experiment, the method of admittance modeling is validated on SPICE with the *inclusion of active control* of the SPICE structure. Although the ALI and Zenith Star flight experiment structures are not now envisioned as actively controlled, there is considerable value in establishing this technology ahead of need.

5.4.2.2 Zenith Star Requirements

The same Zenith Star requirements are addressed here as are discussed in the previous section. In the ALI ground test, the structural disturbance due to coolant flow to and within the secondary mirror has been identified as requiring better characterization than is now available. The Zenith Star flight experiment is required to place a high intensity beam on distant targets. Therefore, it must project a beam from its beam expander that has low jitter and good wavefront quality. The system must be designed so that the sources of disturbance that induce vibration into the structure do not produce distortions in the optical train that degrade the beam below the performance criteria. Although the current Zenith Star flight experiment design does not include active structural control, experience has shown that missions with stressing requirements often have been found during development to need technologies that were not thought necessary in the earlier design stages. Active as well as passive vibration suppression techniques may be required to reduce the effects of the disturbances upon the outgoing laser beam. The selection of the parameters of disturbance suppression techniques must be guided by accurate information about the magnitude and character of the disturbances. Provision of a method for accurately characterizing the effect upon the outgoing HEL beam of coolant flow in a cooled optical element is a Zenith Star requirement that derives from the target engagement goals of Zenith Star. Furthermore, rapid retargeting and active tracking require jitter control which in turn implies a requirement that major sources of jitter be well characterized.

5.4.2.3 Flow-down to SPICE

Admittance modeling is to be used here to predict the effect upon a large actively controlled flexible structure of coolant flow through a mirror. The data needed are obtained from measurements made with

coolant flowing through a rigidly mounted mirror surrogate and from calculations performed using the Zenith Star structural model. The SPICE structural model and existing structure can be used as a stand in for Zenith Star in verifying the characterization procedure. Measurements made with the cooled component actually mounted to the SPICE apparatus can then demonstrate the validity of admittance modeling predictions on a large flexible structure. Validation of the method with active control systems operating on SPICE is a second major step toward demonstrating its quantitative applicability to Zenith Star.

5.4.2.4 Conceptual Design

Overview: The aim of this experiment is to demonstrate by experiment the use of admittance modeling for prediction of flow-induced vibration in a complex structure. The experiment will include the acquisition of sufficient data to predict the mount-point forces from the mirror when it is connected to either the SPICE structure or the Zenith Star structure (or any structure for which an accurate finite element model is available). The active control system can be treated as another connected subsystem with its own admittance model.

Description of Experiment: As Figure 5.4.2.1 indicates, the difference between this and the previous experiment is the inclusion of another set of measurements, namely, that set required to characterize the active control system. The admittance model is obtained from four data sets.

1. The element to be tested, i.e., the surrogate secondary mirror with its fluid supply plumbing, is hard mounted to a rigid base at the points at which it would be attached to the Zenith Star or SPICE structure. Coolant is forced via a pump or a blowdown device from a cooling cart through the coolant flow channels in the surrogate optical element at pressures and flow rates of interest. The (three-dimensional) mount forces are measured using transducers at the attachment points and their auto- and cross-spectral densities are recorded.
2. With the fluid flow turned off and the mirror suspended free-free, artificial excitation of the mirror and fluid supply system permits measurement of the motion/force admittance matrix at the mount points.
3. The motion/force admittance matrix at the mount points of the structure that is to receive the cooled mirror is obtained using the finite element model. For the SPICE structure, this matrix could also be acquired from direct measurements, but it is desired to establish a paradigm that can be applied when the main structure is available only as a finite element model.

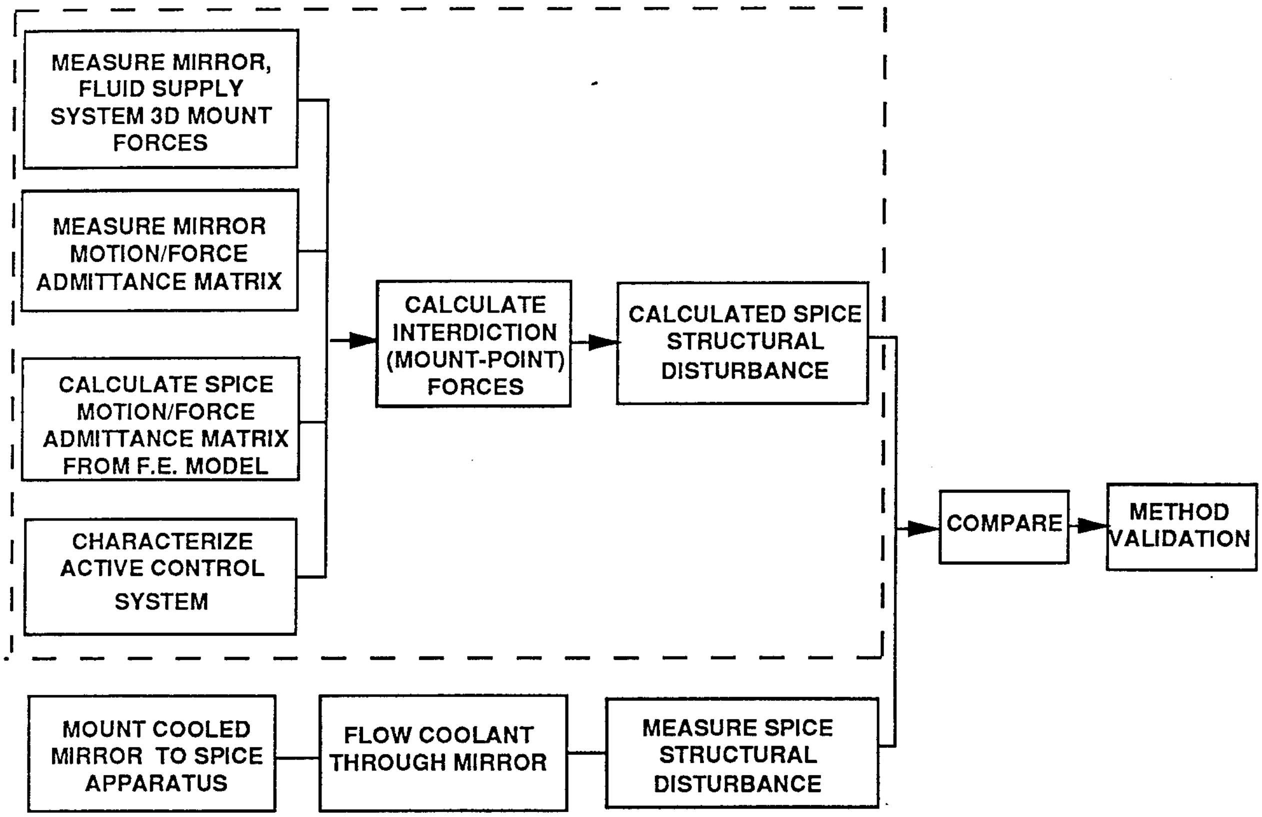


Figure 5.4.2.1 Characterization of Active Control System

4. The active control system is modeled as a frequency response matrix in which rows and columns correspond to actuator and sensor degrees of freedom. For computational reasons, the frequency response matrix is in the force/motion or impedance form rather than the motion/force or admittance form used for the other disturbances.

These data suffice to characterize the effect of the coolant flow disturbance on the SPICE structure. Direct measurements of the combined system response are then made and compared to those calculated from the system admittance model. With the method validated on SPICE, the effect of coolant flow in the same secondary mirror on the Zenith Star structure can be obtained by repeating the part of the procedure enclosed in the dashed box in Figure 5.4.2.1, with the Zenith Star structural model replacing that of SPICE.

5.4.2.5 Determination of SPICE Adequacy

The SPICE structure needs only to be modified to permit attachment of the cooled secondary mirror surrogate. It is already an excellent stand-in for Zenith Star in this experiment.

5.4.2.6 Additional Hardware/Software/Facilities

No additional equipment is required for this experiment if the admittance modeling on a passive structure (see Section 5.4.1) is done first. If it is not, the following items are required :

1. A cooled secondary mirror surrogate.
2. A rigid base to which to mount the cooled element for admittance model data taking.
3. A cooling cart or equivalent.
4. Transducers and recording devices for the off-structure data gathering.

5.4.2.7 Cost Estimates

Total cost of the passive damping of mirror mount modes experiment is estimated to be $80K.

5.4.2.8 Schedule Estimates

The estimated calendar time for this experiment is 5 months (after completion of passive truss admittance model experiment).

5.4.2.9 Benefits to Zenith Star

Accurate characterization of coolant flow disturbances to the ALI and Zenith Star beam expanders will reduce risks on each of them. Should active control become part of the Zenith Star structure, tradeoffs concerning jitter and wavefront error suppression techniques and parameters will have accurate quantitative information about a major source of distortion that is, at present, only semiquantitatively characterized.

The method proposed is sufficiently flexible that future changes to the Zenith Star structural design will not require further coolant flow characterization experiments.

5.4.3 Computational Fluid Dynamics Model to Predict Coolant Flow Disturbances

5.4.3.1 Objective

For both Zenith Star and ALI, one of the key factors driving the secondary support design as well as the jitter control design is the dynamic force disturbance produced by the secondary coolant flow. Section 5.4.1 considers the problem of characterizing the structural response to the coolant flow disturbance.

This section reviews present methods for predicting coolant flow forces and suggests the testing of simple analysis tools for understanding the nature of this critical input disturbance in the context of Zenith Star/ALI support experiments described in Section 5.4.1.

5.4.3.2 Zenith Star Requirement

Figure 5.4.3.1 shows the connection of the coolant flow plumbing to the secondary manifold and thereby illustrates three areas of interest in flow disturbance characterization, namely:

1- Coolant flow forces exerted by the cooled secondary on the secondary support structure. These results also apply to other cooled mirrors in the Zenith Star beam train.

2- Coolant flow forces exerted on the secondary support struts at the attach points of the coolant plumbing.

3- Coolant forces exerted at bends of the coolant plumbing.

Currently the main disturbance force is due to the mirror itself, and this disturbance is estimated by either scaling measured data or by modeling the flow with the United Technologies Optical Systems proprietary model. As mentioned above in Section 5.2.1.2, the predictions vary by more than an order of magnitude. Yet Zenith Star, ALI, and other HEL beam control programs need to anticipate the coolant flow disturbances to produce realistic mechanical and controls designs.

5.4.3.3 Flow-Down to SPICE

Sections 5.4.1 and 5.4.2 describe experiments using the SPICE facility with a secondary mirror coolant manifold (surrogate secondary mirror). Though the experiments provide an excellent opportunity to characterize the response of the structure to a specific disturbance, one would also need to estimate the disturbance independently rather than depend on the measurements from a single specialized coolant manifold. To illustrate the diversity of manifolds, consider the following options often employed in manifold concept development.

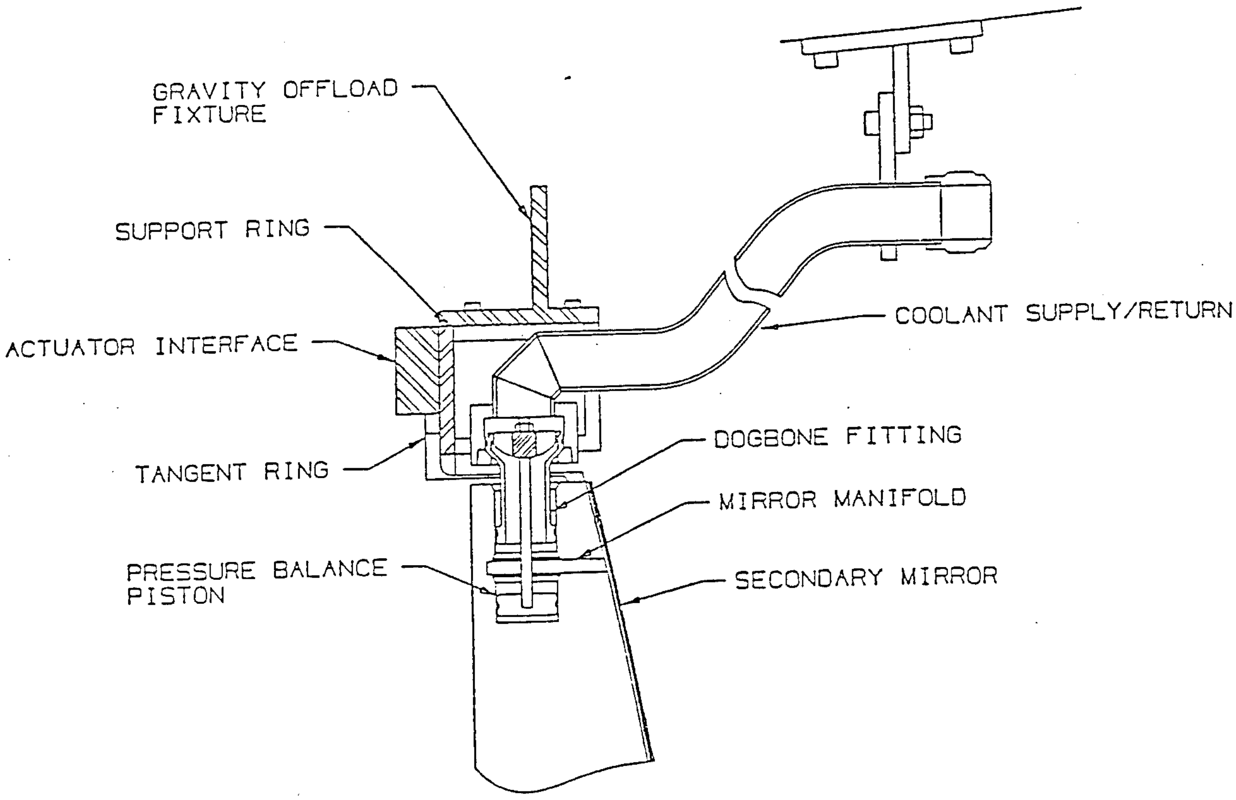


Figure 5.4.3.1 ALI Coolant Plumbing

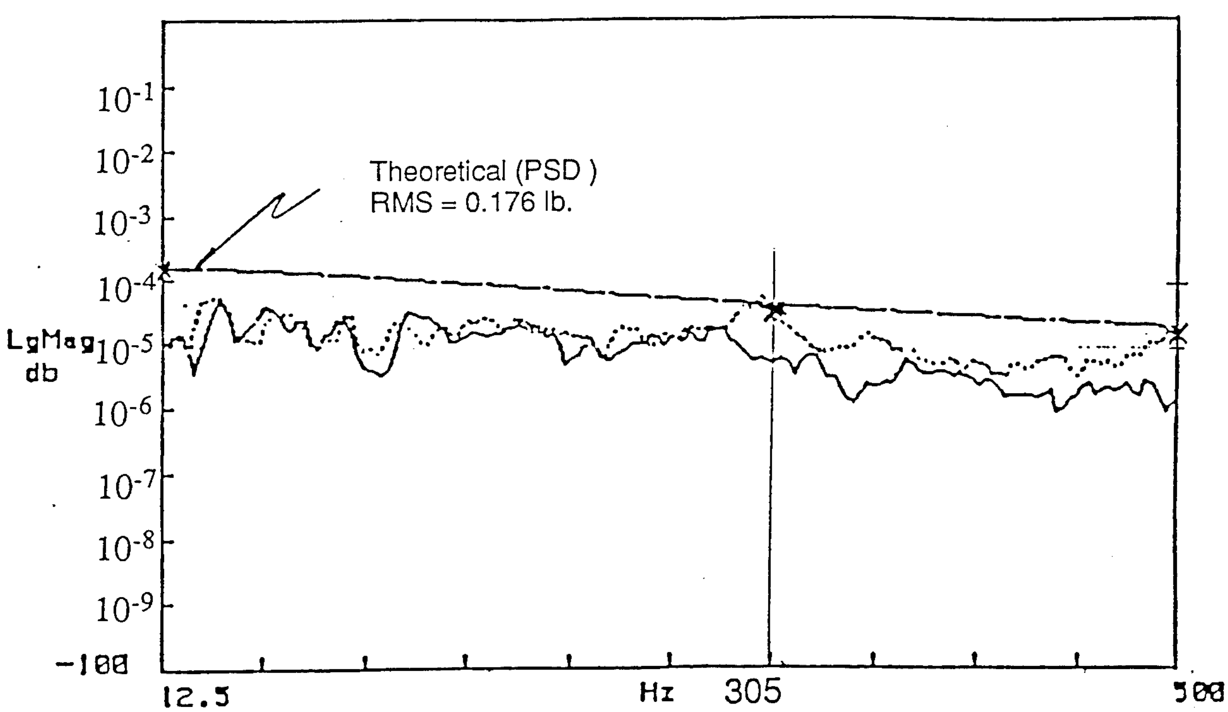
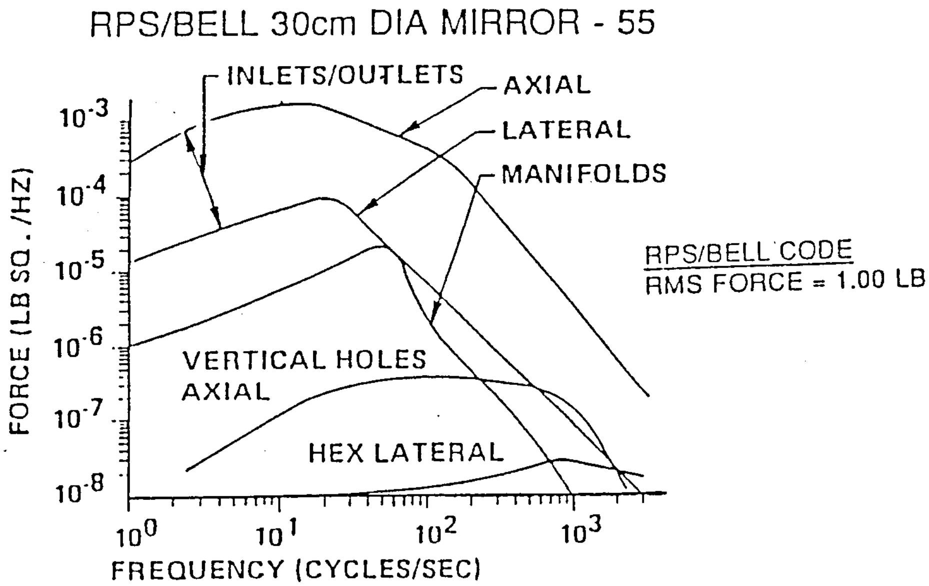


Figure 5.4.3.2 TRW Regression Model



The Bell/RPS model predicts disturbance due to various components of the mirror heat exchanger.

Figure 5.4.3.3 Rockwell Power Systems/Bell Model

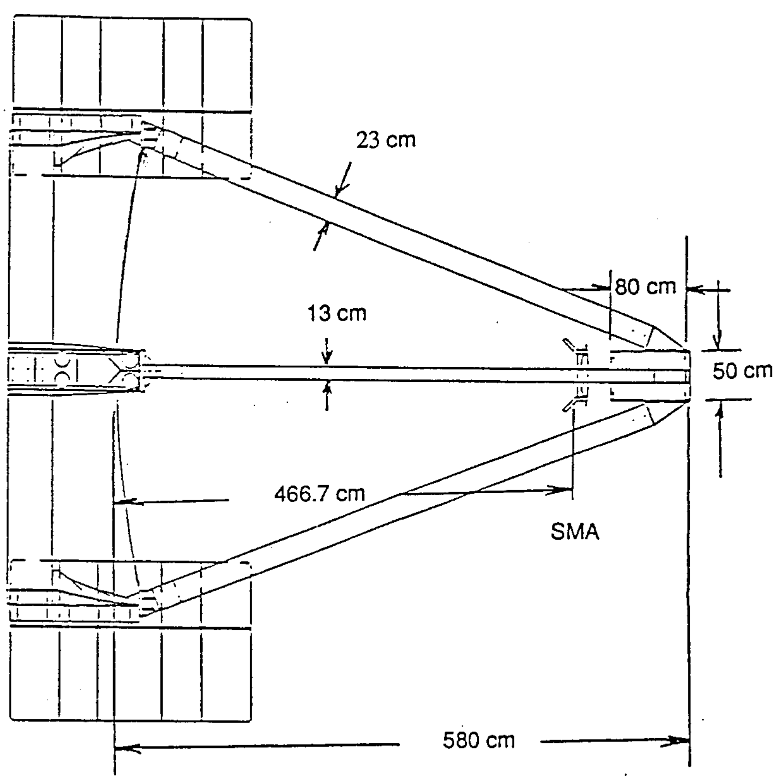


Figure 5.4.3.4 ALI Quadropod Secondary Support Structure

1- Channels vs. posts (Rockwell Power Systems/Bell),
2- Single inlet vs. spaghetti inlet,
3- Foam at inlet and exit,
4- Critical parameters (channel diameter, flow rate, coolant density, dissolved gas, i.e., tubing, tiedowns, bends, etc.).

Each design option has its own force and torque power spectral densities.

Currently, there are three models for predicting coolant flow disturbances. These models are associated with the three corporations United Technologies Optical Systems, TRW, and Rockwell Power Systems/Bell which maintain or have developed the codes. The simplest is that of TRW, which is an empirical regression estimation based on a few critical parameters. Figure 5.4.3.2 shows a comparison of TRW predicted and measured data. Subsequent upgrades of the model predict the peak between 10 Hz and 100 Hz. Bell developed a more detailed model (Figure 5.4.3.3) based on wall pressure power spectral density measurements by Bull and Norton (1976). The Bell model, now maintained by Rockwell Power Systems, is more versatile in the sense that it predicts disturbances due to individual components and also due to bends in the input/output plumbing. United Technologies Optical Systems has proprietary models, which are similar to those of Rockwell Power Systems/Bell in their ability to predict component effects.

SPICE, with the addition of a secondary coolant manifold, provides an ideal testbed for anchoring the coolant flow models, and especially for developing approaches for minimizing the coolant flow disturbance. The difficulty in characterizing turbulent coolant flow justifies an experimental approach for risk reduction, but effective experiment definition requires qualitative and quantitative information which can best be provided by coolant flow models.

5.4.3.4 Conceptual Design

A useful coolant flow experiment might proceed in the following manner:

1- Design and fabricate secondary coolant manifold (simulate ALI since design is most mature).
2- Predict coolant flow forces and torques using the three currently available models.
3- Measure coolant flow forces and torque of secondary manifold mounted on bench, and compare with predictions. Vary as many parameters as possible to determine sensitivity.
4- Simulate the ALI coolant flow plumbing on the SPICE structure and compare results with predictions of the Rockwell Power Systems/Bell and possibly the United Technologies Optical Systems models. Modify to optimize plumbing layout.

5- Perform an integrated experiment (admittance model) as described in Section 5.4.1.

6- Repeat the above procedure for the Zenith Star design as details become available.

As a result of this process, the manifold and plumbing disturbances would be determined for ALI and Zenith Star risk reduction, a definitive comparison of flow models with each other and with a real system would be completed, and hopefully a modeling procedure would be anchored which would provide a realistic prediction tool for future systems.

5.4.3.5 Determination of SPICE Adequacy

The SPICE facility does not now have a cooled mirror surrogate or coolant flow plumbing in the tripod. The remainder of the structure is an excellent stand in for Zenith Star and ALI.

5.4.3.6 Additional Hardware/Software/Facilities

The ALI secondary support design employs a quadrapod structure with coolant (Figure 5.4.3.4) input piped along a pair of opposing struts and coolant output along the opposite pair. To be completely faithful to this configuration, SPICE would need a new secondary support, but that is not necessary to obtain the information sought in this investigation. Simulation of the ALI manifold would require fabrication or perhaps use of a prototype if such exists, and there are pumps or blow-down equipment available at the Weapons Laboratory. We are aware that if a blow-down system is used, we need to make sure that dissolved gasses are not present to adversely influence the data.

5.4.3.7 Cost Estimates

The experimental procedure described above requires installation of plumbing on the SPICE apparatus. However, if the experiment of Section 5.4.1 were already performed,only a test of the fluid dynamics codes would remain to be done. The cost estimate for this study, therefore, includes only model studies and assumes that the experimental results needed to validate simulation results have already been acquired.

The total cost of the investigation of the use of computational fluid dynamics modeling to predict coolant flow disturbances is estimated to be $40K.

5.4.3.8 Schedule Estimates

The effort will require about seven calendar weeks. It could not, of course, be completed before data to validate the results becomes available through, e.g., the completion of the admittance model experiments. Part of this task could be performed as an intercode comparison exercise which would have considerable value on its own. As seen from the cost table, the effort would be about the same, because only 0.5 man-week is estimated to be required for the comparison of experimental data to calculated results.

5.4.3.9 Benefits to Zenith Star

The benefit to Zenith Star and, indeed, to any space-based laser program would be immense if a tool were to be devised that could calculate the forces due to coolant flow in a structure from flow and structure design parameters. The need to proceed by engineering reckoning or even by specific experimental characterization of a structure by admittance modeling would vanish. It is not anticipated that such a huge result could follow from this modest effort, but it would be a vital first step in that direction and it would certainly point the way for the next step toward the goal of learning to characterize accurately what is now probably the most poorly characterized of the important structural disturbances on a directed energy weapon system.

6.0 ASSESSMENT OF VALUE OF EXPERIMENTS TO ZENITH STAR

The subtask has a requirement that the proposed experiments be assessed as to their value in support of the Zenith Star Program. Zenith Star has undergone redirection with the result that neither the flight experiment nor CSE is a subject of current activity. ALI is the focus of effort on that program at this writing. It is against this background that the ratings were made. It is not surprising, therefore, that conceptual designs of experiments to help with possible future necessary modifications to the flight experiment are not rated highly. That design is, after all, not undergoing evaluation and modification at this time.

Experiment	Rating	Comment
1.0 Isolation	**2**	
1.1 Passive isolation of an space based laser component	Low	Already understood well enough for Zenith Star
1.2 Isolation of a beam expander	Medium	Of potential use to a CSE or SLE
1.3 Further SAVI research	High	Vital to success of Zenith Star flight exp.
2.0 Pointing/Tracking Control	**4**	
2.1 Active control of primary mirror segments	Low	Within scope of ALI
2.2 ALI PM-SM alignment system	Medium	
2.3 High performance slewing of beam exp	Medium	Best of 2.0: application to Zenith Star flight
2.4 Separate aperture tracker effects	Low	Not important - optical boresighting is used
2.5 Smart struts in Zenith Star beam expander	Low	Zenith Star has no obvious need of this
3.0 Adv. Materials / Passive Damping	**3**	
3.1 Advanced Composite Materials	High	Useful in design of damped structures
3.2 Passive damping of tripod modes	Medium	ALI will apparently require this technology
3.3 Passive damping of mirror mounts	Low	If set, forget inadequate, would go active
4.0 Disturbance Characterization	**1**	
4.1 Admittance Modeling - passive structure	High	Very important to both flight exp. and ALI
4.2 Admittance Modeling -active structure	Low	Zenith Star flight experiment not an active structure
4.3 Coolant flow disturbances from computational fluid dynamics	High	Very important to both flight experiment and ALI

Table 6.1. Assessment of value of proposed experiments to support Zenith Star.

It is believed that the most relevant assessment of the value of the proposed experiments to the current Zenith Star Program are those shown in Table 6.1. It was done by the Assistant Program Manager/Technical of Zenith Star. Experiments are rated high, medium, or low in value to Zenith Star and the categories are ranked one through four.

7.0 Conclusion

The foregoing rating serves as a summary of this report. All experiments are listed there together with comments as to their success in meeting the goal of this subtask, namely, to support the aims of the Zenith Star Program. The selected approach of SPICE subtask 02-05 was to include every reasonable idea for an experiment, even if its use to Zenith Star was a bit conjectural. Programs typically undergo changes and ALI and Zenith Star may at some future time perceive a need for some of the technologies that are rated "Low" in Table 6.1. It is for that reason that it was thought worthwhile to assemble here all of the ideas generated on this subtask.

REFERENCES

1. Conceptual Design Drawings and Associated Lists,CDRL A002 for SPICE Subtask 02-04/00, Optical Scoring System Design, Report No. F284266, Lockheed Missiles and Space Co., Albuquerque, NM, September 1990.

2. Landesman, B. T., Linear Wavefront Analysis Using the Aberrations of Tilted and Decentered Systems, Report No. F284404, Lockheed Missiles and Space Co., Albuquerque, NM, October 1990.

3. Breakwell, J. A., "Optimal Feedback Slewing of Flexible Spacecraft", Journal of Guidance and Control, Vol 4, No. 5, pp. 472-479, September-October 1981.

4. Aspinwall, D. A., "Acceleration Profiles for Minimizing Residual Response", Journal of Dynamic Systems, Measurement, and Control, Vol 102, pp.3 - 6, March 1980.

5. Schoenwald, D. A., Feddema, J. T., Eisler, G. R., and Segalman, D. J., Minimum-Time Trajectory Control of a Two-Link Flexible Robotic Manipulator, Paper submitted to the 1991 IEEE International Conference on Robotics and Automation, Sacramento, CA, April 1991. (unpublished)

6. Kienholz, D. A., Feasibility of a Pneumatic, Floor-Standing, Gravity Offload for the SPICE Facility, Report No. 89-08-02, CSA Engineering Co., Palo Alto, CA, August 1989.

LIST OF ACRONYMS AND ABREVIATIONS

AAA	Alignment annulus assembly
ALI	Alpha/LAMP Integration
C	Celsius
CG	Center of gravity
CSE	Complementary Space Experiment
F	Fahrenheit
HAC-LAC	High authority controller - low authority controller
HEL	High-energy laser
HOE	Holographic optical element
HZ	Hertz
I	Moment of inertia
LAMP	Large Advanced Mirror Program
N	Newtons
OSS	Optical scoring system
OWS	Outgoing wavefront sensor
PM	Primary mirror
RMS	Root-mean square
SAVI	Space Active Vibration Isolation
SBL	Space-based laser
SDI	Strategic Defense Initiative
SLE	Space Laser Experiment
SM	Secondary mirror
SMJT	Secondary Mirror Jitter Test
SPICE	Space Integrated Controls Experiment
cm	centimeter
db	decibel
deg	degree
in	inch
kg	kilogram
lb	pound
m	meter
mm	millimeter
mrad	milliradian
s	second

LIST OF ACRONYMS AND ABREVIATIONS (CONCLUDED)

μm	micrometer
μrad	microradian